Some Unique Propagation Characteristics of Linearly Graded Multilayered Planar Optical Waveguides

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Abstract- **The properties of guided light in linearly-graded refractive index profile planar optical waveguides with *multilayered structure* are studied in view of their unique characteristics. Towards exact analysis, we perform mode-calculation of the given waveguide structures using a formulation with Airy functions devised with the exponential ones as solutions to Helmholtz's equation. First, we confirm the efficacy of our analysis by applying appropriate solution schemes to a few known waveguides having such linearly-graded index profiles that are studied and reported in the literature with quoted results. Then we visit the field confinement properties of such multilayered waveguides that are sensitive to various structural parameters. We demonstrate the progressive field penetration in low-index core region and single-mode operation at high core-depth as useful properties with unique advantages. These characteristics are particularly relevant in accessing guided field, in sensing and in controlling modal propagation in guided wave devices. The study should be useful to design and explore new devices for applications in integrated optics.**

Keywords- Linearly Graded Index Waveguide; Mode Effective Index; Mode Field Distribution; Multilayered Waveguide; Confinement Factor

I. INTRODUCTION

Significant advantages over the conventional step-index planar structure have made the graded-index (GRIN) profile waveguide a valuable member of the guided-wave photonic circuits. Out of a variety of known index profiles, namely, parabolic [1], exponential [2], Gaussian [3], linearly graded waveguides [4] possess unique features over these competing counterparts. Besides the main use of linearly graded waveguides in shifting the waveguide dispersion [4] (which is true for all graded-index structures), such linear graded refractive index (RI) guiding medium has the credential to reduce the propagation loss and provides minimal modal attenuation in comparison with various GRIN profile waveguides having similar structural parameters [5]. This fact has been utilized in developing evanescent-wave based chemical sensors [5]. Furthermore, waveguides with linear gradation of RI can also be deployed in effectively guiding CO_2 laser light (λ=10.6 μm) [6]. Chiasera *et. al.* [7] evaluated the Brillouin spectra, which is used to estimate the velocity of sound in the waveguide and obtained exciting results for such structures. They compared the outcomes with conventional homogenous waveguides. Notably, Kerr waveguides having linear RI profile are extensively studied for local [8] and non-local [9] propagation characteristics of solitons in the structure. In view of the above mentioned versatile characteristics of linearly graded guiding geometry, we performed a detailed study of the guided modes of linearly graded MPWG using an analytical approach. For analysis of the guiding mechanism of light through such waveguides, several methods [10-15] including approximate, numerical and analytical recipes were used to investigate a variety of linearly graded structures. Approximate and numerical techniques having limitations in exactly describing the propagation characteristics, we followed analytical approach for exact solutions [15] in order to determine precisely the waveguide modes. We have studied the dependence of the mode effective indices and modal field distributions of the scalar modes on various structural parameters for practical linearly graded waveguides. The step index Multilayer Planar Waveguide (MPWG) enjoys many advantages over the conventional three layered structure (substrate-film-cover) namely, light confinement in the low index region [16], possible tailoring of field confinement, single mode behaviour in the large core depth (~20 μm) and with high index contrast [17]. Furthermore, step-index MPWG has interesting applications in the field of optical modulators, semiconductor laser, directional couplers etc [18]. Both linear and non-linear effects [19-21] in step index MPWG have been extensively studied in the past. But to the best of our knowledge, graded index MPWG [22, 23] has not been explored thoroughly for many such applications. Motivated with this fact, we undertook the task of an extensive study of the modal properties of such linearly graded MPWG. Interestingly, we worked with two key structural parameters (number of layers and ratio of high- to low-index core width, K) to control the field distribution that provides additional advantages of such linear RI profile waveguide.

In this article, we first describe the basic equations and expressions for structural geometries, followed by a few case studies towards analysing a relatively complex multilayered structure. In doing so, we first consider a three-layer linearly graded guiding structure for investigating the dependence of core-width(s) on either side of the waveguide-axis, RI of the substrate and cover on the distribution of modal field across the waveguide. In the subsequent section, we detail our analysis of guided modes and corresponding field distributions of an N- layer linearly graded RI profile waveguides. We have demonstrated that the field confinement can be tailored by varying the number of layers and the ratio of the widths of high-index triangular core to the low-index space between two successive triangular core in both single-mode and multi-mode regimes. We have also observed that by incorporating few low-index layers (a minimum of two) within the core with small K values, one can obtain single-mode operation for a large core waveguide. These results are new in planar waveguide research and will help exploring new applications in integrated optic devices.

II. THE ANALYSIS FORMULATION AND RESULTS

The scalar field distribution $\Psi(x)$ of an optical waveguide satisfies the Helmholtz's equation which, for planar waveguides under weakly guiding approximation, can be expressed as [24],

$$\frac{d^2\Psi(x)}{dx^2}+\left(k_0{}^2n^2(x)-\beta^2\right)\Psi(x)=0 \tag{1}$$

where $n^2(x)$ represents the refractive index (RI) profile and β $(= k_0 neff)$ is the effective index of the scalar mode. The mathematical representation for the RI of a three-layer linear waveguide structure can be expressed as:

$$\begin{aligned} n^2(x) &= n_1{}^2\left(1-2\Delta\frac{|x|}{a}\right) & |x|\le a \qquad \Delta=\frac{n_1{}^2-n_2{}^2}{2n_1{}^2} \\ &= n_2{}^2 & |x|\ge a \end{aligned}$$

Here, a is the core width and n_1, n_2 are the core and cladding refractive indices respectively. The Helmholtz's equation can be reformulated, with a shift in the co-ordinate of the core (from x to P) as:

$$\frac{d^2\Psi}{dP^2}-P\Psi=0 \quad |x|\le a \quad where\ P=\frac{D^{3/2}|x|-C^2}{D}, C^2=k_0{}^2n_1{}^2-\beta^2, D=\left(2k_0{}^2n_1{}^2\frac{\Delta}{a}\right)^{2/3}$$

$$\frac{d^2\Psi}{dP^2}-\gamma^2\Psi=0 \quad |x|\ge a \quad where\ \gamma^2=\beta^2-k_0{}^2n_2{}^2$$

Now, the solution in the core for such equation can be represented in terms of Airy functions, whereas the conventional exponential function correctly represents the solution in the cladding. Thus,

$$\begin{aligned} \Psi(x) &= A_\pm A_i(P)+B_\pm B_i(P) & |x|\le a \\ &= C_\pm e^{-\gamma|x|} & |x|\ge a \end{aligned} \tag{2}$$

where '±' denotes the field amplitudes along the +ve and –ve direction. Now for a guided mode, the tangential field amplitudes have to be continuous across the interfaces where derivatives of RI suffer a change [15]. This leads to the eigenvalue equation yielding the guided modes. For a multilayered structure, this procedure is implemented to all the interfaces and the continuity equations constitute a co-efficient matrix whose vanishing determinant provides the mode solution. In the following sections we discuss a few typical waveguides and results of the particular situation. Then, we study multilayer waveguides with linearly graded RI profiles and discuss the results pertaining to our analysis.

A. *Three-Layer Linearly Graded-Index Planar Waveguides*

As a first case, we study the modal characteristics of linearly-graded index waveguide and the influence of different structural parameters on the modal propagation. We consider the simplest three layered waveguide with linear variation of RI in the core (shown in Fig. 1).

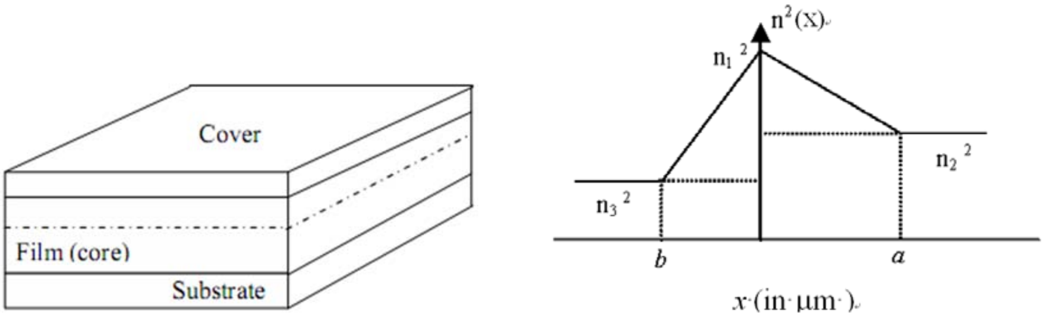

Fig. 1 Schematic diagram and refractive index distribution of linearly graded planar waveguide

The RI profile for such waveguide can be represented as,

$$
\begin{aligned}
n^2(x) &= n_1^2\left(1-2\Delta_1\frac{x}{a}\right) && 0\le x\le a && \Delta_1=\frac{n_1^2-n_2^2}{2n_1^2}\\
&= n_1^2\left(1+2\Delta_2\frac{x}{b}\right) && -b\le x\le 0 && \Delta_2=\frac{n_1^2-n_3^2}{2n_1^2}\\
&= n_2^2 && x\ge a &&\\
&= n_3^2 && x\le -b &&
\end{aligned}
$$

Here, n_1, n_2 and n_3 are the refractive indices at the centre of the core, substrate and cover respectively. This type of refractive index profile can approximately be obtained by varying the mole fraction of Ag+ ions in the $AgNO_3$- $NaNO_3$ solution during the fabrication of waveguides following the technique of ion-diffusion in BK-7 glass [25]. The parameters used in the analysis are n_1 = 1.504452, n_2 = 1.500652, a =15 μm and λ = 1.55 μm. Using the formulation described above, we determined the mode effective indices and the corresponding modal field-distribution of the waveguide. By varying the two associated structural parameters- the 'width-asymmetry' factor as $a_W = [a^2 \sim b^2]/ [a^2+b^2]$ and 'RI-asymmetry' factor as $a_R = [n_2^2-n_3^2]/ [n_2^2+n_3^2]$ respectively for such waveguides, we study the effect of these parameters of the modal field profiles (see Figs. 2 and 3). Both the figures show the shifting nature of peak value of the field amplitude with the width-asymmetry factor, a_W and RI-asymmetry factor, a_R. Keeping the a_R at a large value (≈0.38, for n_3=1), we observed that the peak of the field shifts slowly towards the core-cover interface with the increasing a_W, which corresponds to a small reduction in confinement. However, with fixed a_W (= 0), and increasing a_R the peak value of field shifts towards the cover by a larger amount (in comparison with the previous case), since it tends to bring down the inhomogeneity in RI. This is indicative of a quantitative estimate of selective control of peak shift of field and its penetration into the low-index region.

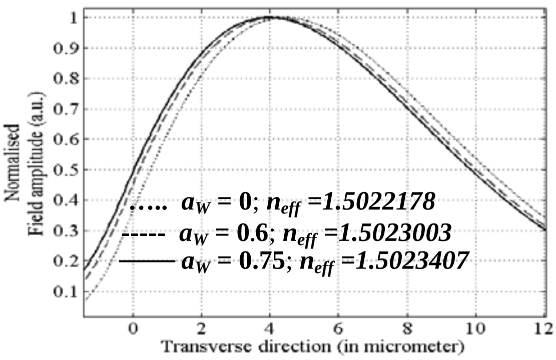

Fig. 2 Dependence of fundamental field distribution on width asymmetry factor (a_W)

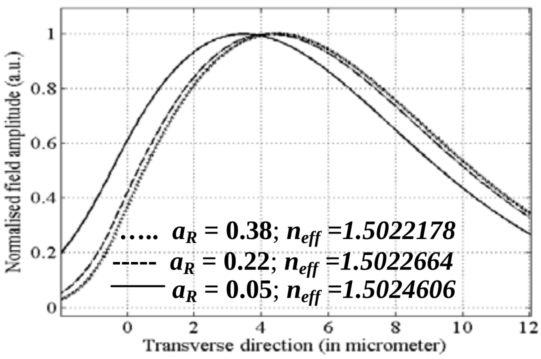

Fig. 3 Dependence of fundamental field distribution on RI asymmetry factor (a_R)

Next, we evaluated the dispersion characteristics of the fundamental and first order modes for different values of a_W and a_R of this waveguide. The results are plotted in Figs. 4 and 5. With increasing a_W and decreasing a_R, the effective indices of various order modes are seen to increase.

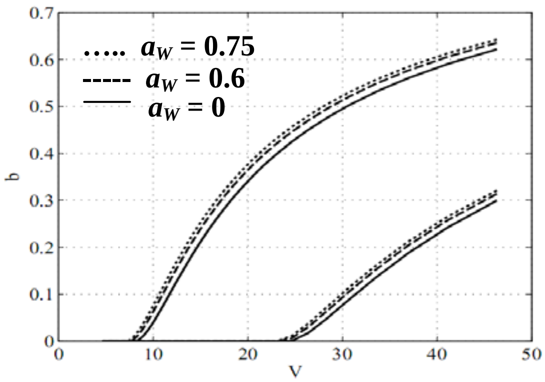

Fig. 4 Computed dispersion curves of fundamental mode and first order mode for different asymmetric-width factor (a_W)

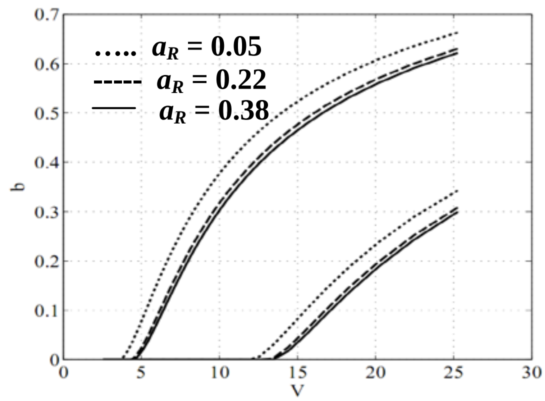

Fig. 5 Dispersion curves of fundamental mode and first order mode calculated for different asymmetric-RI factor (a_R)

B. Four-Layer Asymmetric Linearly-Graded Index Planar Waveguide

Next, we consider a multilayered planar waveguide with linearly varying RI in each layer which is in general asymmetric in nature. Such waveguides find use in guiding beams from CO_2 laser having wavelength ~10.6 μm [6]. In reference [6], this waveguide is studied. Using our mode-calculation algorithm, we also determine the guided modes of this waveguide and compare the results with the reported one [6]. Following the same notations used in Ref. [6], we express the refractive index profile of the structure as,

$$\begin{aligned} n^2(x) &= n_c^2 && x\le 0 \\ &= n_f^2 && 0\le x\le T \\ &= n_f^2\left(1-2\Delta\frac{x-T}{d}\right) \quad \Delta=\frac{n_f^2-n_s^2}{2n_f^2} && T\le x\le T+d \\ &= n_s^2 && x\ge T+d \end{aligned}$$

The corresponding RI profile is plotted in Fig. 6. In [6], three distinct parameters were introduced, we have intentionally kept these parameters unchanged for straight comparison and those are given as:

$$a_E=\frac{n_s^2-n_c^2}{n_f^2-n_s^2} \qquad V=k_0(T+d)\sqrt{\left(n_f^2-n_s^2\right)} \qquad b=\frac{\beta^2-k_0^2n_s^2}{k_0^2\left(n_f^2-n_s^2\right)}$$

The physical solution of the scalar Helmholtz equation for different layers of such a waveguide can be expressed as

$$\begin{aligned} \psi(x) &= Ae^{\gamma_C x} && x\le 0 \\ &= B\cos ux + C\sin ux && 0\le x\le T \\ &= E\,A_i(P)+F\,B_i(P) && T\le x\le T+d \\ &= Ge^{-\gamma_S x} && x\ge T+d \end{aligned} \tag{3}$$

$$where \quad \gamma_c^2=\beta^2-k_0^2n_c^2,\ u^2=k_0^2n_c^2-\beta^2, D=\left(2k_0^2n_f^2\frac{\Delta}{d}\right)^{2/3}, C^2=k_0^2n_f^2-\beta^2+2k_0^2n_f^2\Delta\frac{T}{d}$$

$$\gamma_s^2=\beta^2-k_0^2n_s^2,\ P=\frac{D^{3/2}x-C^2}{D}$$

Now, to represent a mode, we consider the electric field and its normal derivative to be continuous across every interface of the waveguide. By putting all these continuity conditions, we have obtained a co-efficient matrix. For mode solution, the determinant of this matrix must be zero, i.e.

$$\begin{vmatrix} 1 & -1 & 0 & 0 & 0 & 0 \\ \gamma_c & 0 & -u & 0 & 0 & 0 \\ 0 & \cos(uT) & \sin(uT) & -A_i\,(P)_{=T} & -B_i\,(P)_{=T} & 0 \\ 0 & -u\sin(uT) & u\cos(uT) & -A_i{'}(P)_{=T} & -B_i{'}(P)_{=T} & 0 \\ 0 & 0 & 0 & A_i\,(P)_{=T+d} & B_i\,(P)_{=T+d} & -e^{-\gamma_s(T+d)} \\ 0 & 0 & 0 & A_i{'}(P)_{=T+d} & B_i{'}(P)_{=T+d} & \gamma_s e^{-\gamma_s(T+d)} \end{vmatrix} = 0$$

The dispersion curves and modal field distribution for this type of waveguides for the first two modes (*m=0* and *m=1*), using two different values of a_E and λ, have been plotted and are shown in Fig. 7 and Fig. 8 respectively.

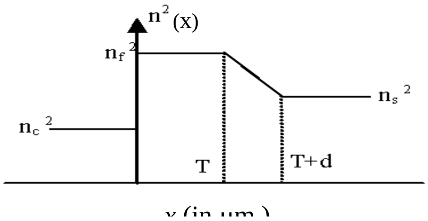

Fig. 6 The RI distribution of asymmetric multilayered planar waveguide

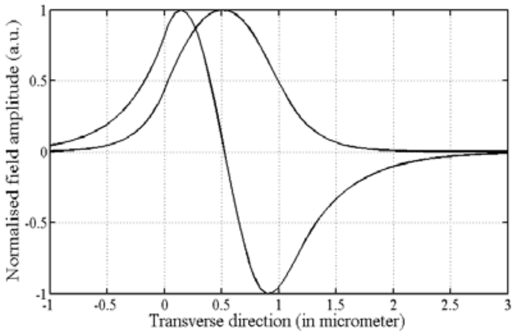

Fig. 7 Field distribution of asymmetric planar waveguides for d/T=0.5, λ=10.6 μm and a_E=0.125

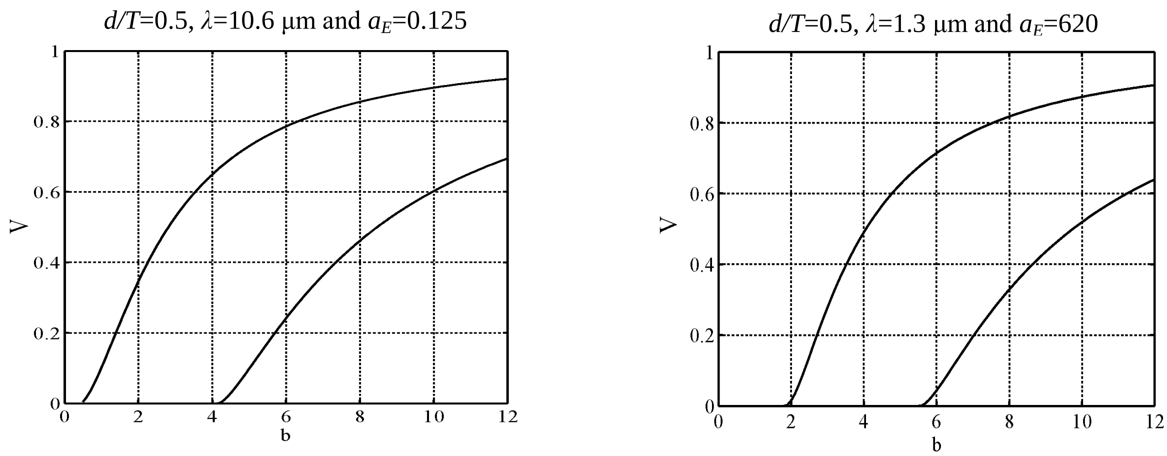

Fig. 8 b vs V plot for asymmetric multilayered planar waveguides different asymmetry factor

C. *Multilayered Linearly Graded Index Planar Waveguide*

Finally, we consider the situation where the waveguide is periodic in nature and the refractive index distribution of each high-index layer is linearly graded. In our study, we have kept the width of every alternate layer having constant high/low refractive indices a. Mathematically, the RI variation for such kind of linearly graded multilayer waveguide of width R, where core is divided into N number of regions can be represented as,

$$
\begin{aligned}
n^2(x) &= n_1^2\left(1-2\Delta\,\frac{|x|}{a}\right) && 0\le |x| \le a && \Delta = \frac{n_1^2-n_2^2}{2n_1^2}\\
&= n_2^2 && a\le |x| \le a+b\\
&= n_1^2\left(1+2\Delta\,\frac{|x|-(2a+b)}{a}\right) && a+b\le |x| \le 2a+b\\
&= n_1^2\left(1-2\Delta\,\frac{|x|-(2a+b)}{a}\right) && 2a+b\le |x| \le 3a+b\\
&\;\vdots\\
&= n_2^2 && |x| \ge R
\end{aligned}
$$

The typical RI distribution has been depicted in Fig. 9.

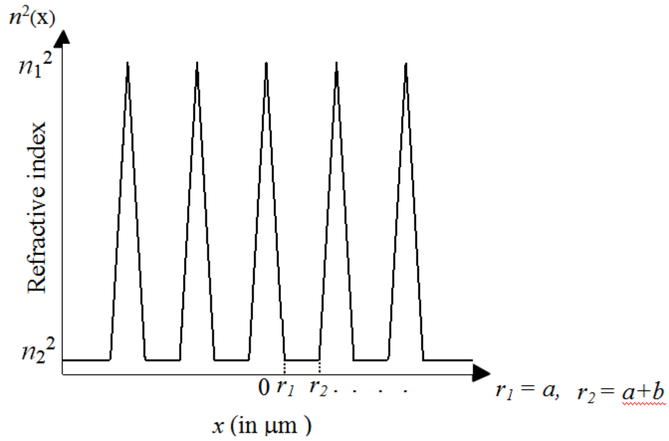

Fig. 9 The RI distribution of symmetric linearly graded multilayered planar waveguide

Here, for the sake of simplicity of calculation, we have considered the origin at the centre of the waveguide. We have also assumed identical RI of the cover and substrate. But one can impose the asymmetry between them by incorporating a minor change in the above mentioned definition of RI profile. The solution of the Helmholtz's equation for such RI variation can be evaluated for each layer as,

$$\begin{aligned}
\psi(x) &= A_{\pm}A_i(P_1) + B_{\pm}B_i(P_1) && 0 \le |x| \le a \\
&= C_{\pm}\,e^{-\gamma|x|} + D_{\pm}\,e^{\gamma|x|} && a \le |x| \le a+b \\
&= E_{0\pm}A_i(P_2) + F_{0\pm}B_i(P_2) && a+b \le |x| \le 2a+b \\
&= E_{1\pm}A_i(P_3) + F_{1\pm}B_i(P_3) && 2a+b \le |x| \le 3a+b \\
&= G_{\pm}\,e^{-\gamma|x|} + H_{\pm}\,e^{\gamma|x|} && 3a+b \le |x| \le 4a+b \\
&\;\vdots \\
&= I_{\pm}\,e^{-\gamma|x|} && |x| \ge R
\end{aligned}$$

$$\begin{aligned}
P_i &= \frac{(-1)^{i+1}D^{3/2}x - C_i^{\,2}}{D} \\
C_1^{\,2} &= k_0^{\,2}n_1^{\,2} - \beta^2; \\
C_2^{\,2} &= k_0^{\,2}n_1^{\,2} - \beta^2 - k_0^{\,2}n_1^{\,2}\frac{2\Delta}{a}(2a+b); \\
C_3^{\,2} &= k_0^{\,2}n_1^{\,2} - \beta^2 + k_0^{\,2}n_1^{\,2}\frac{2\Delta}{a}(2a+b); \\
&\;\vdots \\
C_{2i+1}^{\,2} &= k_0^{\,2}n_1^{\,2} - \beta^2 + k_0^{\,2}n_1^{\,2}\frac{2\Delta}{a}i(2a+b) \quad \text{where } i = \text{integer} \\
C_{2i}^{\,2} &= k_0^{\,2}n_1^{\,2} - \beta^2 - k_0^{\,2}n_1^{\,2}\frac{2\Delta}{a}i(2a+b)
\end{aligned} \tag{4}$$

Here, the parameters P_i and γ inside the argument of the solution have been calculated treating each layer separately and following the same procedure discussed in Section 2. Subsequently, by applying the continuity conditions of the field amplitudes at each of the interfaces, we evaluated the co-efficient matrix and thereafter we obtained modes of various order.

For a fixed width (R) and fixed ratios (K) of high-index and low-index regions within the core, one can easily deduce a relation between the width of high-index ($2a$) or low-index (b) region and the total number of layers (N). The relations take the forms as,

$$2a = \frac{4RK}{K(N+1)+(N-1)};\; b = \frac{4R}{K(N+1)+(N-1)} \tag{5}$$

1) Mode-Field Distribution and Its Variation with Different Structural Parameters:

Using the above relations for the mode solutions, we calculated the mode indices along the corresponding field distribution of a nine-layer (N =9) linearly graded structure with fixed width (R= 45 µm). The results are plotted in Fig. 10 for different values of K (all other parameters are identical to the ones used in *case I*). As seen in the Fig. 10, with the increment of high RI core width ($2a$) over low RI one (b) which is responsible for the increment of K, the field confinement appears to increase. This is because higher width of core assimilates more light into it. However, since the total width (R) is fixed, at high/low K regime, the change in K will modify $2a$ or b by very small amount and as a result it increases the possibility of saturation of the field confinement within the core. So, within the moderate limit only (0.05 to 20), increment of K will increase the field confinement, although the actual quantifications are possible from the estimation of confinement factor for such structures.

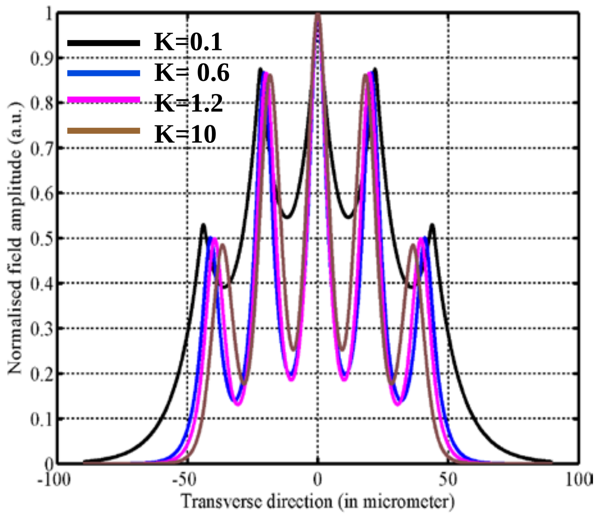

Fig. 10 Computed fundamental mode-field profile of a nine-layer linearly graded planar waveguide with R = 45 µm

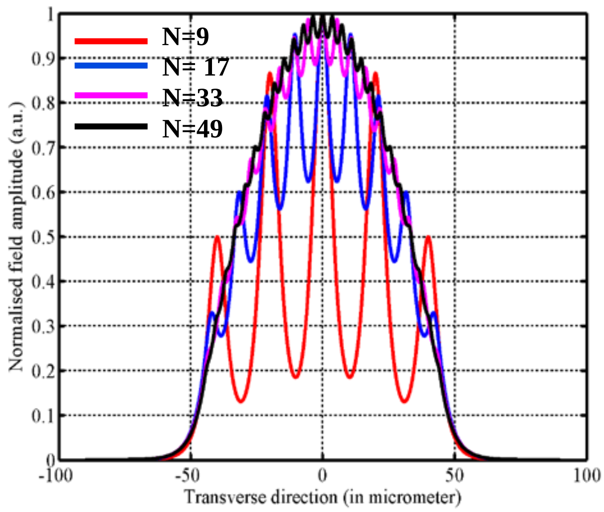

Fig. 11 The fundamental mode-field distribution of a linearly graded planar waveguide with R = 45 µm and K=1

In Fig. 11, we have used the number of layers as a parameter to study the fundamental mode field distribution of a linearly graded planar waveguide keeping K a constant quantity (K=1) for a fixed core width of 45 µm. Since, from Fig. 11, it seems difficult to infer about the variation of the mode-field confinement for various values of N, we evaluated the confinement factor for each structure, which is discussed in the following section.

2) Mode Field Confinement:

From the results that we observed in Fig. 10 and Fig. 11, we then calculate the confinement factor for varying the associated geometrical parameters of the structure. Now, starting from Equation (4), one can evaluate the confinement factor (Γ) from various high-index core (HIC), low-index core (LIC) layers and cladding as,

$$\Gamma=\frac{\int_0^{depth}\psi^2{}_{Core}dx}{\int_0^{\infty}\psi^2{}_{Total}dx}=\frac{\int\left(\psi^2{}_{HIC}+\psi^2{}_{LIC}\right)dx}{\int_0^{\infty}\psi_{Total}{}^2dx}$$

$$\psi_{HIC}=A_{HIC}A_i\left(\left|P_{HIC}\right|\right)+B_{HIC}B_i\left(\left|P_{HIC}\right|\right)$$

$$\psi_{LIC}=A_{LIC}e^{-\gamma_{LIC}|x|}+B_{LIC}e^{\gamma_{LIC}|x|}$$

$$\psi_{Cladding}=A_{Cladding}e^{-\gamma_{LIC}|x|}$$

$$\int\psi^2{}_{HIC}dx=\frac{1}{\sqrt{D}}\int\left(A_{HIC}A_i\left(\left|P_{HIC}\right|\right)+B_{HIC}B_i\left(\left|P_{HIC}\right|\right)\right)^2dP_{HIC}$$

$$=\frac{1}{\sqrt{D}}\left[A_{HIC}{}^2\left\{P_{HIC}A_i^2\left(P_{HIC}\right)-A_i'^2\left(P_{HIC}\right)\right\}+B_{HIC}{}^2\left\{P_{HIC}B_i^2\left(P_{HIC}\right)-B_i'^2\left(P_{HIC}\right)\right\}+2AB\left\{P_{HIC}A_i\left(P_{HIC}\right)B_i\left(P_{HIC}\right)-A_i'\left(P_{HIC}\right)B_i'\left(P_{HIC}\right)\right\}\right]$$

$$\int\psi^2{}_{LIC}dx=\int\left(A_{LIC}e^{-\gamma_{LIC}|x|}+B_{LIC}e^{\gamma_{LIC}|x|}\right)^2dx=A_{LIC}{}^2\frac{e^{-2\gamma|x|}}{2\gamma}+2A_{LIC}B_{LIC}|x|+B_{LIC}{}^2\frac{e^{2\gamma|x|}}{2\gamma}$$

$$\int\psi^2{}_{Cladding}dx=\int\left(A_{Cladding}e^{-\gamma_{LIC}|x|}\right)^2dx=A^2{}_{Cladding}\frac{e^{-2\gamma|x|}}{2\gamma}$$

$$\int_0^{\infty}\psi^2{}_{Total}dx=\int_0^R\psi^2{}_{Core}dx+\int_R^{\infty}\psi^2{}_{Cladding}dx$$

Using the above relations, we compute the confinement factor Γ for this structure with different parameters. The outcomes from such studies can be inferred as: in the multimode region (R= 45 µm) and for afore-mentioned moderate values of K, with increasing *N* the field confinement will decrease. This can be explained as follows: the effective regions of both the low- and high-index are altered with increasing number of layers (*N*) in the core. Unlike the low-index part, region occupied by the high-index will decrease with the increment of *N*. As a result, confinement of light within the multilayered core will decrease. However, the change of the high- and low-index regions is proportional to width of the core (R). But, for higher values of R, any significant change in the confinement of light with increasing *N* will not be noticed. This is because of the fact that most of the light will be captured by the central high-index region. So, in order to observe any appreciable change in the confinement of field its width has to be reduced. Moreover, while exercising the field confinement analysis we marked the possibility of a higher range of tailoring the guided field for small values of *K* (<1) in the multimode regime. This happens because the effective index of the core changes by a higher amount.. Since, very small values of *K* will saturate the confinement (previously mentioned), therefore, to get a better range of tailoring confinement, it becomes obvious to shift to the single-mode region with small core width (*R*). Additionally, the single-mode structure is also a necessary requirement of lasing as higher order modes cannot lase, and multilayer waveguide structures are enormously used in fiber lasers applications [27].

3) Optimization towards Single Mode Operation of Linearly Graded Multilayered Waveguide:

We have evaluated the number of modes for varying widths of the waveguide structure where number of layers (*N*) and the ratio of the width of high to low RI region, *K* as the two key parameters. In this calculation, all other parameters are kept the same as in the **Case I**. First, we investigated the dependence of cut-off width (c_R) for single mode operation on the number of layers, *N* for a fixed value of *K* (=1). This yielded critical width of the core, c_R which is found to be around 6-7 µm (Fig. 12). Then, we varied *K* progressively to a very high value (~ 20) to check whether it has any effect on c_R or not. Interestingly, we find that when *K* varies from 1 to 20 (moderate range of *K*), the waveguide will be in single-mode regime if its width is around 5 µm for a very large number of layers. Thereafter, we investigated the *K* and *N* dependence on confinement, Γ.

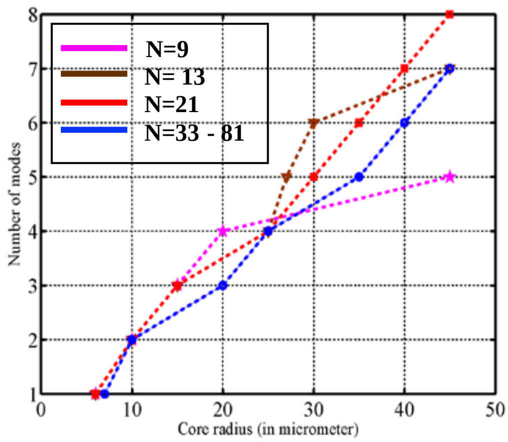

Fig. 12 Dependence of number of modes on the core-width for K=1

Optimization of the core-width for the waveguide to operate in the single-mode regime has been obtained in the following way: the core-width, beyond which the waveguide becomes multimode, is estimated first by varying the number of layers, N and keeping K as a fixed parameter. Subsequently, the same procedure repeated with different values of K in order to obtain the optimized value of core-width (c_R ~ 5 μm) for which the waveguide transmits only the fundamental mode-field for a moderate range of K and N. Now, with this optimized value of c_R (= 5.0 μm) for single-mode operation, we have determined the confinement factor (Γ) of the fundamental mode for different values of K using N as a parameter. As expected from the Fig. 10, we obtained an increasing nature of the confinement factor with increasing values of K for a fixed value of N. This is plotted in Fig. 13. However, as seen from Fig. 14, it is evident that the modal field-confinement can also be tailored up to 5% by changing N only using moderate values of K (~ 0.1) which can support practical dimension. Also, from Fig. 14, one can see that for a fixed value of K, with increasing number of layers in the waveguide core, the field in the low-index region will be more as a result of incorporating additional high RI layers. However, the effective index of the core will be reduced (which was minimal in multimode regime) and this will cause more light field to flare out in the cladding. Initially for small values of N, the effect of low RI dominates as a result the field confinement decreases, but then the interplay of the two effects will saturate the confinement for higher number of layers [17]. Through this exercise, we have achieved the confinement up to 83% for K=10 but beyond which the field confinement does not improve significantly (see Fig. 13). The study also reveals that by incorporating additional layers in the waveguide core *i.e.*, a minimum of two low RI regions with N=5, *the single-mode regime can be obtained for large core-width for very small values of K (K ~ 0.001 will suffice for 20 μm core-width)*. This unique property adds many advantages namely, bending insensitivity; easy and effective light confinement in using such structure.

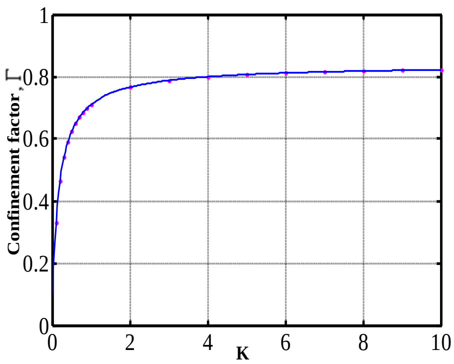

Fig. 13 Confinement factor Γ as a function of K with N as a parameter

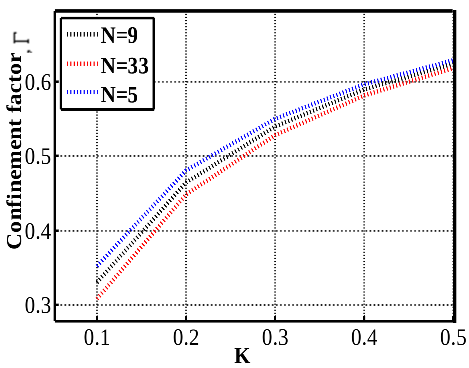

Fig. 14 Confinement factor Γ as a function of K with N as a parameter

III. CONCLUSIONS

In this paper, we have discussed propagation characteristics of guided modes in linearly graded RI profile multilayered planar waveguides. Starting with the analysis of simple triangular RI profile structures with geometrical and optical asymmetries, we investigated relatively complex multilayered structures in view of their structural dependence towards light-guiding properties. We demonstrated that for moderate values of K (0.05-20), light confinement in the low-index core can be modulated significantly with number of layers of the structure in multimode regime, which can be utilized in selectively accessing guided field for sensing/decoupling applications. Furthermore, we have also illustrated that in the single-mode region the light confinement within the core can be tailored (~ 5%) notably by increasing number of layers, N. A maximum confinement ~ 83% has been achieved under single-mode operation for K=10. Single mode waveguides with large width of core can be obtained by incorporating additional layers in the core. These findings are new and can help in designing and exploring new devices in the integrated optics.

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