Optics Communications 284 (2011) 1202–1207

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Discussion

Analysis of buried parabolic index segmented channel waveguides with z-dependent profile

Ruchi Garg *, M.R. Shenoy, K. Thyagarajan

Department of Physics, Indian Institute of Technology Delhi, Haus Khas, New Delhi 110016, India

A R T I C L E I N F O

Article history:
Received 15 June 2010
Received in revised form 19 October 2010
Accepted 24 October 2010

Keywords:
Graded index waveguides
Channel waveguides
Segmented waveguides

A B S T R A C T

We analyze, to the best of our knowledge, for the first time buried parabolic index segmented channel waveguides, with high-index segments having a z-dependent refractive index variation. Using the standard ABCD ray transfer matrices for Gaussian beam propagation, we obtain the dependence of effective index, spot-size, amplitude and phase fronts of the guided modes on various waveguide parameters. Stability conditions are obtained for various cases. The analysis is used to study segmented waveguides fabricated using femtosecond laser inscription method; the experimentally observed dependence of stability on the duty cycle of segmentation is explained.

1. Introduction

Segmented waveguides consist of a linear array of high-index regions in a homogeneous (low index) substrate, and have been extensively studied for various applications. Due to the possibility of achieving simultaneous domain inversion and guiding, such waveguides have been studied for non-linear interactions utilizing quasi phase matched (QPM) schemes [1–3]. Easy manipulation of the duty cycle of segmentation extends its application to linear waveguide devices such as mode expanders, polarization converters and Bragg reflectors [4,5]. Segmented waveguides are also employed as mode adapters to improve coupling efficiency [6], and as sensors [7] owing to the flexibility in controlling the waveguide geometry, which in turn would alter the sensitivity of the device. Recently, buried segmented waveguides found their application in designing of a multimode interference phased array structure (MMI PHASAR) which greatly reduced the area occupied by the configuration thereby playing a vital role in the field of optical communication [8].

There are many techniques to realize buried segmented waveguides including those using double exchange process (annealed proton exchange (APE) followed by reverse proton exchange) and femtosecond laser inscription [9–11].

Most analytical investigations that have been reported deal with planar segmented waveguides [12,13] while numerical techniques for analyzing the properties of segmented waveguides have also been reported [14,15]. Since segmented waveguides have guidance in both the transverse dimensions, it is necessary to analyze segmented channel waveguides. Further, in techniques involving diffusion or femtosecond laser inscription, the high-index segments themselves have a refractive index variation that depends on the longitudinal coordinate as well. Thus it is important to analyze segmented channel waveguides with z-dependent high-index segments and to be able to determine the variation of effective index of the modes and the modal spot-size, and the regions of stability with various parameters of the segmented waveguides.

In this paper, we analyze infinitely extended parabolic index segmented waveguides in which the high-index segments have a parabolic refractive index variation along the transverse directions (x and y), with the gradation parameters also having a z-dependence (see Fig. 1). Using the standard ABCD ray transfer matrices for Gaussian beam propagation [16] we obtain the dependence of effective index, spot-size, amplitude front and phase front of the mode on various waveguide parameters. Stability conditions for light guidance have also been discussed. The analytical results of the segmented waveguide are useful to understand the general features of three dimensional graded index segmented waveguides. Although the analysis is for infinitely extended parabolic index segments, the analysis can be used to predict the general features of propagation in graded index segmented waveguides.

2. Analysis

Assuming the propagation direction to be the z-direction, the segmented waveguide made up of infinitely extended parabolic high-index regions is described by the following equation:

$$\begin{aligned} n^2(x,y,z) &= n_0^2(z)\left\{1-\alpha^2(z)x^2-\theta^2(z)y^2\right\} && 0<z<d \\ &= n_2^2 && d<z<\Lambda \end{aligned}$$

* Corresponding author.
E-mail addresses: ruchigarg19@gmail.com (R. Garg), mrshenoy@physics.iitd.ac.in (M.R. Shenoy), ktrajan@physics.iitd.ac.in (K. Thyagarajan).

0030-4018/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.optcom.2010.10.083

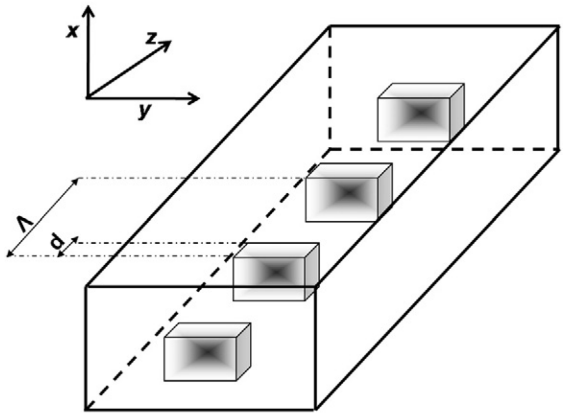

Fig. 1. Schematic representation of buried segmented waveguide.

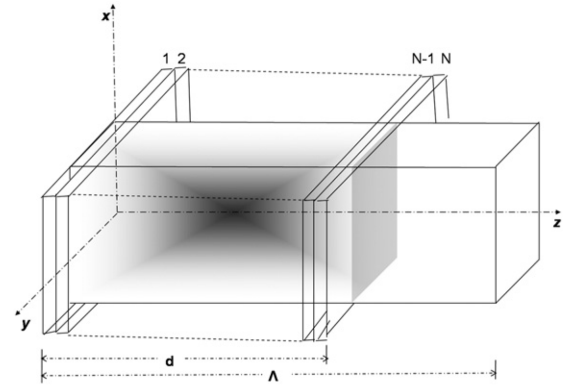

Fig. 2. Schematic depicting one period of the segmented waveguide wherein each graded high-index segment is divided into N sub-segments of uniform refractive index.

with

$$n^2(x,y,z+\Lambda) = n^2(x,y,z)$$

where α and θ are measures of gradation of the parabolic refractive index profile in the x and y-directions, respectively, $n_0(z)$ is the z-dependent axial refractive index of the high-index segment, n_2 is the refractive index of the substrate, d is the length of high-index segment along the propagation direction, and Λ is the periodicity of segmentation. In general, the grading parameters α and θ could be different and could also be functions of z. To be specific, we assume the z-dependence to be Gaussian which could realistically represent segmented waveguides produced by indiffusion, ion exchange or femtosecond laser inscription. Thus we write

$$n_0(z) = n_2 + (n_1 - n_2)\, exp\left\{-\frac{(z-d/2)^2}{d_0^2}\right\} \tag{1}$$

$$\alpha(z) = \left[\frac{\alpha' + C_1\, exp\left\{-\frac{(z-d/2)^2}{d_0^2}\right\}}{\Lambda}\right] \tag{2}$$

$$\theta(z) = \left[\frac{\theta' + C_2\, exp\left\{-\frac{(z-d/2)^2}{d_0^2}\right\}}{\Lambda}\right]. \tag{3}$$

In the above equations, n_1 is the (maximum) refractive index at the midpoint of the high-index segment, α' and θ' are the normalized gradation parameters i.e. $\alpha' = \alpha(C_1=0)\Lambda$; $\theta' = \theta(C_2=0)\Lambda$, and d_0, C_1 and C_2 are constants.

Since the high-index segments have a parabolic transverse refractive index variation, we assume the fundamental mode of the segmented waveguide to have an "elliptic Gaussian" transverse distribution [17] and define the parameters of the Gaussian mode by the fact that the mode distribution would repeat itself in amplitude and phase after one period of segmentation. We analyze Gaussian beam propagation through the segmented waveguide under paraxial approximation by employing ABCD law of ray transfer matrices [18]. To include the z-dependence of the refractive index, we divide the high-index parabolic medium into sufficiently small sub-segments, each of width dz such that we can assume each sub-segment to have uniform refractive index (see Fig. 2).

Thus, the transition matrix for the Gaussian beam from the n^{th} sub-segment to the $(n+1)^{\text{th}}$ sub-segment along z-axis is given by [19]:

$$M_x(n) = \begin{bmatrix} 1 & 0 \\ 0 & \frac{n_0(\zeta_n)}{n_0(\zeta_{n+1})} \end{bmatrix} \begin{bmatrix} cos\alpha(\zeta_n)dz & \frac{sin\alpha(\zeta_n)dz}{\alpha(\zeta_n)dz} \\ -\alpha(\zeta_n)dz\, sin\alpha(\zeta_n)dz & cos\alpha(\zeta_n)dz \end{bmatrix} \tag{4}$$

where $\zeta_i = (i - \frac{1}{2})dz$; $i = 1,2,\ldots,N$.

The argument ζ_n refers to the z coordinate of the n^{th} sub-segment at its midpoint. If the high-index segment is divided into N sub-segments, then the ABCD matrix for the Gaussian in the x-direction for one period of the segmented waveguide is given by:

$$\begin{bmatrix} A_x & B_x \\ C_x & D_x \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & \frac{n_2}{n_0(\zeta_1)} \end{bmatrix} \begin{bmatrix} 1 & \Lambda - d \\ 0 & 1 \end{bmatrix} \times M_x(N) \times M_x(N-1)\_\_\_M_x(2) \times M_x(1) \tag{5}$$

where the subscript x refers to the fact that the ABCD matrix corresponds to the x-direction. The first matrix on the RHS represents refraction at the interface and the second matrix represents propagation through the homogeneous region of refractive index n_2. In case of the y-direction, α gets replaced by θ.

In order to determine the modes of the segmented waveguide structure, we launch an elliptic Gaussian beam and use the condition that the beam should reproduce itself after one period. This will give us the Gaussian mode of the waveguide. Using this Gaussian mode we calculate the phase accumulated over one period from which we can deduce the effective index of the mode. Field distribution at a particular distance can be determined from the given beam and the ABCD matrix corresponding to the medium [16]. In our analysis, we have neglected the reflections at the interfaces due to the small index differences between the various segments. These reflections could become important when Bragg condition for constructive interference between different reflected waves is satisfied. However, the period that we have chosen is far from the Bragg condition and hence the effect of reflection loss is not significant. Higher order modes are given by Hermite–Gaussian field distributions, which form a complete set of orthogonal functions.

Thus the incident field distribution is assumed to be:

$$U_1^{mn}(x,y,z=0) = U_{0x}^m(x)U_{0y}^n(y) \tag{6}$$