Abstract

Key words: *Integrated Optics, Lithium Niobate, Ti:LiNbO$_3$, Beam Propagation Method (BPM), Semi-analytical method, optical waveguide, directional coupler, coupled waveguide, refractive index profile, effective index, propagation constant, mode profile, matrix method, EIMM, bending loss, coupling length, overlap integral, electro optic, switch, electrode, buffer layer, periodically segmented waveguide (PSW), cut-off wavelength, asymmetric directional coupler, tunable filter, integrated optic amplifier, Erbium diffusion, proton exchange, wet etching, ridge waveguide.*

In this thesis a novel semi-analytical method named the Effective-Index-based Matrix Method (EIMM) has been applied to the modal analysis of graded-index channel waveguides like that formed by Titanium indiffusion in Lithium Niobate substrate (Ti:LiNbO$_3$) and coupled waveguide systems. Some experimental studies on diffusion of Erbium (Er) in LiNbO$_3$ and their characterisation for realising integrated optic amplifier and selective wet etching of LiNbO$_3$ following proton exchange to form ridge waveguides have also been carried out.

A review of the different methods for analysis of integrated optic structures has been made as a back up for the work undertaken in the thesis (Chapter-2). For the sake of completeness, a brief outline of the basic theory of wave propagation in optical waveguides is given in the chapter. This is followed by a review of the numerical and semi-analytical methods. Efforts have been made to make the review up-to-date.

The Effective-Index-based Matrix Method (EIMM) has been developed and applied for the determination of the modal profiles of graded index channel waveguides for different propagation modes (Chapter 3). The matrix method [12], which was earlier used for analysis of 2D planar waveguides has been directly applied to 3D waveguides like Ti:LiNbO$_3$ channel waveguides whose 2D variation of refractive index has been transformed into 1D effective refractive index profile using WKB method [13,14. This 1D effective refractive index profile for a particular mode is discretised into a layered structure, and then the matrix method is applied to evaluate the electric field in different layers for the given polarisation of the input light. The propagation constant for each mode is subsequently determined very precisely. The

relative values of electric field and intensity are then computed in the different layers. Although computations have been performed for TE and TM polarisations and compared with the experimental results of Ti:LiNbO$_3$ waveguides fabricated in-house, the method in principle can be used for any type of waveguide and for any arbitrary polarisation of light. The progressive multiplication of 2x2 transfer matrices is the only major computational step in the entire method. This makes this method very fast compared to the conventional numerical methods.

The method (EIMM) has also been successfully applied for finding the propagation characteristics of directional couplers and other multiwaveguide structures (Chapter 4). For a device formed by more than two waveguides, power can be coupled via any of the waveguides. In such a situation, the concept of overlap integral has been introduced to obtain the modal profiles along propagation direction. The results of computation of modal characteristics of Ti:LiNbO$_3$ coupled structures at different propagating distances have been obtained, and some computed results are compared with measured profiles of fabricated structures.

The EIMM simulation of a directional coupler electro optic switch has been done (Chapter 5). The electrooptically induced change in refractive index is computed using analytical expressions for electric field distribution available in the literature derived by solving Laplace's equation [20] and using the method of image when a buffer layer is used [21], in combination with the electro-optic equations. The variation of refractive index profile depends upon the type and dimensions of electrodes and their relative position and also on the buffer dielectric layer thickness. The optical power distribution along the coupled region for different values of applied voltage and hence the switching voltage have been computed by applying EIMM. Computations were performed on Ti:LiNbO$_3$ directional coupler switches with suitable electrodes. The simulated results are found to match well with available experimental results [22-26] and other BPM/FEM [27,28] numerical simulation results obtained from literature.

EIMM has also been extended to the analysis periodically segmented waveguides (PSWs) formed in Ti indiffusion in LiNbO$_3$ (Chapter 6). The Ti-concentration profiles and the induced refractive index changes of Ti:LiNbO$_3$ PSWs have been computed for different waveguide dimensions and fabrication parameters, at the design wavelength, using approximate analytical models. The effective index profile of the PSW is obtained by averaging the contributions from different regions along the segments. EIMM is then applied to compute propagation constants of the PSWs. The cut-off wavelength of PSW has been computed as a function of duty cycle keeping the period constant. This PSW when used as one arm of an asymmetric directional coupler (ADC), with the other arm formed by continuous waveguide, can *be used as a tunable filter. PSW when used in one arm of ADC filter changes the two-step photolithographic process into a single step.*

Finally, some experimental work on the fabrication of waveguides in $LiNbO_3$ substrate is presented (Chapter 7). Ti indiffused waveguides and coupled waveguides were fabricated in the laboratory and the measured intensity profiles for single-mode waveguides and coupled waveguides have been compared with theoretical results obtained using EIMM. Some experimental studies have also been undertaken on Er diffusion into the $LiNbO_3$ substrate, which are used for realising integrated optic amplifier and laser [18,19]. Amplifiers and lasers along with other integrated optical components are needed to realise a complete integrated optic system. Some experimental results on the optical characteristics of the Er-diffused layers have been presented in the thesis. The formation of ridges by selective wet etching following proton exchange on the surface of $LiNbO_3$ substrate is also investigated.