ABSTRACT

In recent years, optical network has grown tremendously to fulfill the enormous demand of bandwidth requirements due to remarkable increase of network users and services in nationwide network backbone consisting of nodes. The key devices of network nodes are photonics matrix switch, wavelength division multiplexer/demultiplexer, adaptive equalizer, add/drop multiplexer etc. Traditionally, these devices consisted of bulky and heavy components that require careful alignments, protection against vibrations, moisture and temperature drift. In order to make them compatible with the modern technology, *Photonic Integrated Circuits (PIC)* based on planar waveguide was first coined by S. E. Miller in 1969 for implementation of these devices. The introduction of Photonic Integrated Devices (PID) for applications in high speed optical networks providing multiple services to more number of users is indispensable as this requires large scale integration (LSI) and the miniaturization of PID device components remains a very challenging task.

The basic components of PID are planar waveguide technology based directional coupler (DC), Two-Mode Interference (TMI) coupler and Multimode Interference (MMI) coupler. For PID, it is required to select the components on the basis of issues such as compactness, higher fabrication tolerance, polarization independence and lower power loss. In this thesis, study is carried out on these device components with their new proposed structures considering the above issues.

The introduction of DC, Multimode Interference (MMI) principle and Two Mode Interference (TMI) principle in PID are made in 1969, 1973 and 1977 respectively. Optical Directional Coupler (DC) consists of two dielectric waveguides placed in close proximity to each other for coupling of guided power based on phase difference of two guided modes— even mode and odd mode. On the other hand, the MMI couplers are based on self-imaging principle which is a property by which an input field profile is reproduced in single or multiple images at periodic intervals along the propagation direction of the guide. It consists of a multimode central waveguide section (excitation of more than two modes) with input and output single mode access waveguides. TMI coupler consists of central waveguide (TMI section) with zero waveguide separation gap connected to two input and output single mode access waveguides and power transferred
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to the output waveguides depends on the phase difference between two excited modes – fundamental and first order. In optical networks, DC, MMI coupler and TMI coupler based integrated optic devices, such as Waveguide Division Multiplexer (WDM), add/drop multiplexer, optical switches have been used.

Extensive studies have been made for implementation of such device components using a variety of materials such as Lithium Niobate, polymers, III-V semiconductors and silicon based materials. Out of these materials Silicon (Si) based materials have the potential to allow strong confinement of light with moderately low propagation losses, high index contrast, low material cost and its compatibility with well known conventional silicon based IC technology. The Si based waveguide materials are Silicon-On-Insulator (SOI) (silicon core), SiO₂/SiO₂-GeO₂ (Core) and SiO₂/Silicon Oxynitride (SiON) core. Among these materials Silicon Oxynitride (SiON) as core and SiO₂ as cladding is considered as a promising material for PID as it offers the wide range of refractive index in between 1.45 (SiO₂) to 2.0 (Si₃N₄) providing the auxiliary advantage for high index contrast designs and due to the property of optical transparence from 210 nm to beyond 2000 nm. This optical property has permitted to develop low loss waveguides for long range applications such as nationwide networks, optical waveguide sensor and integrated quantum optical circuits etc.

Apart from the materials, previous authors have reported on studies of different geometries such as tapered geometry (parabolic tapered, linearly tapered at middle, parabolic tapered at middle) and periodic grating structure with different shape for DC, TMI couplers and MMI couplers for more compactness, higher fabrication tolerances etc. Recently, T. Sai et al. have shown tooth shaped grating assisted TMI coupler for wavelength division multiplexing.

Within this frame it is seen that very few studies are made for comparative study of DC, TMI coupler and MMI coupler. M. Rajarajan et al. in 1999, reported a simulation study for performance comparison between DC and MMI coupler using vector finite element and least square boundary residual numerical tools. Further, S. Y. Lee et al. in 2004 has presented a comparison of ridge-type DC and MMI coupler in terms of transformation relationship and coupling characteristics. From the best of our knowledge,
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No existing literature has been found stating comparative study on conventional couplers such as DC with TMI coupler and DC with TMI as well as MMI couplers.

As discussed earlier, development of passive optical compact components (such as DC, TMI coupler and MMI coupler etc.) for large scale integration (LSI) with low insertion loss, low polarization dependent structures so as to reduce polarization dependent loss and higher fabrication tolerance with low crosstalk is very much required. In this Ph. D. work, all these aspects of DC, TMI and MMI based devices have been studied and the prime objectives of this thesis are considered as follows:

I. To develop a mathematical model using Simple Effective Index Method (SEIM) based on sinusoidal modes for accurate estimation of coupling power in directional coupler (DC), Two Mode Interference (TMI) coupler, Multimode Interference (MMI) coupler and find a transformation relationship of DC with TMI coupler and MMI coupler with silica waveguides using silicon oxynitride as a core material.

II. To design a compact TMI coupler using tooth shaped grating assisted geometry for Photonic Integrated Devices. Also design and propose tooth shaped grating assisted Directional Coupler and MMI coupler for compactness.

III. To design double S-bend structures for compact TMI coupler and proposed MMI coupler for PID.

IV. To fabricate the designed DC, TMI coupler and MMI coupler using silica waveguides with silicon oxynitride as a core and characterize it for performance analysis.

In this research effort, a mathematical model using simple effective index method (SEIM), based on sinusoidal mode has been developed for accurate estimation of coupling power in the DC, TMI and MMI couplers. The results obtained using SEIM are found to be accurate and comparable with the other reported results and commercially available simulation tool such as optiBPM. A transformation relationship has been established among these couplers and in addition, the conventional structures of these couplers were fabricated and their experimental results were compared in order to verify
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with the theoretical predictions. Further, tooth shaped grating assisted (GA) geometry have been incorporated in the coupling region of these couplers for reduction of coupling length.

Although it is found that GA-TMI coupler has the shorter beat length than the other two types of optical couplers (GA-DC and GA-MMI), the total device length of GA-MMI coupler is most compact. The beat length of grating assisted couplers are ~50% compact than that of the conventional couplers. In the proceeding chapter of the thesis, double S-bend (DS) structure of TMI and MMI couplers has been studied. The coupling characteristics of DS-TMI coupler and DS-MMI coupler are compared theoretically and experimentally with their conventional geometries. Finally, at the end of thesis work, future scopes and possible application of the current study have been discussed.