Chapter 1

Introduction

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1.1 Introduction

Over the last decades, transmission capacity of communication systems has been grown tremendously. In this direction, electronic technology has not been able to achieve the terahertz speed necessary for the high speed optical networks of present day's communication system. Due to limited speed of electronic components, the capacity of the optical communication systems has become limited [1, 2]. This leads to emerge optical signal processing as a new communication bottleneck over the last few years. To overcome this limitation, all-optical processing has been introduced for signal processing in high speed communication systems. Optical signal processing has been introduced first in 1970 [3]. Since then, optical processing has been made by bulk optics requiring careful alignment, protection against vibration, moisture and temperature drift. In order to make them more compatible with modern technology, integrated optics has been introduced in optical signal processing.

Plasmonics is a well-established and rapidly growing research field with a long history [4]. Although the history of plasmonics can be traced back to 1902 [5], existence of surface plasmon polaritons (SPPs) was first predicted in 1957 [6] and experimentally demonstrated in 1960 [7]. The topic started to gain attraction only in the 1980s when researchers realized the strong confinement of energy at the metal surface [8] and then the research in this field gradually gained momentum through evolution of fabrication and characterization methods enabling studies of SPP at the nanometer dimensions [9].

During the last two decades, there have been extensive theoretical as well as experimental research in the field of SPP devices based on multimode interference (MMI) principle. Use of MMI based SPP device has given a new direction to the study of integrated optic waveguide devices. In this work, we have introduced two-mode interference (TMI) principle in surface plasmonic waveguide to get compact component for integrated optic waveguide devices such as all-optical logic gates and tunable optical power splitter.

1.2 Motivation

In present day's communication system, miniaturization of optical components has become a matter of concern to attain large scale integration of integrated optic waveguide devices. For faster operation of the integrated optic devices, all-optical control of device components has become another essential requirement. High performance all-optical logic gates have become key components in optical computing and networking systems to perform optical signal processing functions such as binary addition, parity checking, header reorganization, all-optical label swapping and data encryption [10]. Optical power splitter is another important component of integrated optic waveguide processor. Tunable optical power splitters are useful for dynamical redistribution and efficient management of optical power in various optical devices. Some of the key issues which motivate us for this research are given below:

- The primary approach is to miniaturize the basic device components as well as having easy fabrication for the use in large scale integrated optical circuits and to achieve all-optical control of the device components.
- Most of the existing approaches for integrated optical processor are unable to provide the all-optical control of logic operations or the compact device dimensions preferred for large scale integration of integrated optical devices.
- Optically controlled tunability of optical power splitting ratio is required for high speed optical processing.
- Two-mode interference (TMI) coupler has become strong candidate for future integrated optic devices due to its many desirable properties such as compactness, large fabrication tolerance and polarization insensitivity in comparison to other components [11].
- Surface plasmon polariton (SPP) based waveguide devices have been able to draw attention due to its compactness and easy fabrication [12, 13].

To the best of our knowledge, very few literatures are available on SPP based two-mode interference waveguide component for integrated optical processor devices. In this work, SPP based two-mode interference coupler has been introduced as a compact component for all-optical logic gates and tunable optical power splitter to achieve compact device size as well as all-optical control over device functionality.

1.3 Research objectives

After a thorough literature survey to study the existing approaches for integrated optical processor device components (in terms of device dimension and mode of operation) and a comparative study of directional coupler (DC), two-mode interference (TMI) coupler and multimode interference (MMI) coupler with silicon based materials, the prime objectives of the research work are considered as follows-

- To design two-mode interference coupler based on SPP waveguide.
  - To reduce the device size.
- To design optical processor device components with the help of the SPP based two-mode interference coupler.
  - To design compact fundamental all-optical logic gates for integrated optical processor.
  - To design compact universal logic gates such as NOR and NAND gates.
  - To design compact, all-optical XOR gate.
  - To design an optically tunable compact power splitter for integrated optical processor.

1.4 Methodology adopted

In order to fulfill the objectives set for the thesis, the following steps have been carried out:

- A thorough literature survey for the existing approaches for integrated optical processor device components (in terms of device dimension and mode of operation).
- Selection of two-mode interference coupler based on surface plasmon polariton as a basic structure of fundamental components for optical processor.
- Mathematical modeling and simulation of the surface plasmonic two-mode interference (SPTMI) coupler with effective index methods.
- Design of compact, all-optical fundamental and universal logic gates with the SPTMI coupler
- Design of optically tunable compact power splitter based on SPTMI coupler.

1.5 Research achievement

In this thesis, two-mode interference coupling in a surface plasmonic metal-insulator-metal (MIM) waveguide is proposed and studied with the help of effective index methods. Based on surface plasmonic two-mode interference coupling in the MIM waveguide, the devices used in integrated optical processor have been designed.

The major contributions of this thesis are given below-

1. A compact surface plasmonic two-mode interference (SPTMI) waveguide coupler has been introduced as a basic component for integrated optical processor devices. It is seen that the length of coupling region required for obtaining cross and bar states is $\sim$ 8.4 times smaller than that in a recently reported previous work. Transition from cross state to bar state is controlled optically by application of optical pulse. The energy of optical pulse required for switching action is $\sim$ 1.3 times smaller than that of the previous work.

2. All-optical fundamental logic operations have been obtained by using the basic SPTMI waveguide coupler. The selection of logic operation (NOT, AND and OR) can be controlled optically by the presence or absence of optical power at the access waveguides. The total length of the SPTMI waveguide coupler based all-optical fundamental logic gates is found to be $\sim$ 5.9 times smaller than that of the previous work for all-optical logic operations, whereas the optical pulse energy required to get logic states is $\sim$ 1.65 times smaller than the previous work.

3. All-optical universal logic gates have been realized by cascading three SPTMI waveguide coupler. By cascading three SPTMI waveguide couplers in two stages, all-optical NOR and NAND logic operations can be implemented simultaneously. Using the same structure, the XOR logic operation is also implemented. The selection of NAND-NOR logic states and XOR logic states is controlled by proper selection of control and input signals.

4. Optically controlled tunable power splitter has been designed by using the basic SPTMI waveguide coupler. The device length of the SPTMI waveguide coupler based 3dB tunable optical power splitter is found to be $\sim$ 1.4 times less than that of a recently published work by previous researchers

on optical power splitter with variable splitting ratio. Tunability of power splitting ratio depends on energy of optical pulse applied on cladding area. By varying the energy of optical pulse, the power splitting ratio can be tuned dynamically over a wide range.

1.6 Thesis organization

The thesis has been organized into six chapters. In the following, the summary of each chapter has been outlined briefly-

Chapter 1: *Introduction*- Chapter one gives a general introduction to the thesis. It gives a brief introduction to integrated optic waveguide devices and explains the motivation and objectives of the thesis.

Chapter 2: *Theoretical foundation and review of SPP based optical waveguide devices*- Chapter two provides a brief overview on the theoretical background and comprehensive literature required to achieve the goals set in the thesis. The chapter presents a review on the planar waveguide couplers and a comparative study among directional coupler, two-mode interference (TMI) coupler and multimode interference (MMI) coupler. It is found from the comparative study that, the TMI coupler provides smaller beat length than that of directional coupler and MMI coupler. For this reason, two-mode interference coupler has been chosen as the basic structure of study in this thesis. The chapter 2 also provides a theoretical background of surface plasmon polariton based waveguides and reviews the existing works on all-optical logic gates and tunable optical power splitter.

Chapter 3: *Two-mode interference coupler based on SPP waveguide*- In chapter three, a compact two-mode interference coupler based on surface plasmonic metal-insulator-metal waveguide is proposed and designed for application in integrated optic waveguide processor. The basic device structure consists of silicon core, silver upper and lower cladding and GaAsInP left and right cladding. The refractive index of GaAsInP shows a nonlinear refractive index change on application of optical pulse energy. When an optical pulse is applied on the GaAsInP cladding area in the device, refractive index modulation of GaAsInP occurs and an additional phase change is introduced between the excited SPP modes propagating through the silicon core. The optical pulse controlled operation of the SPTMI coupler by index modulation in GaAsInP cladding is analyzed mathematically with the help of effective index methods. It is found that the length of two-mode coupling region required to introduce an additional phase change of

π between the SPP fundamental and first order modes, leading to switching of coupling states is $92.35\mu m$. This value is about ~ 8.4 times less than the length of coupling region required to change cross and bar states in a recently reported work by previous researcher. The total device length is found to be $142.29\mu m$ which is about ~ 5.9 times less than that in the previous work. The optical pulse energy required for switching of coupling states is found to be $16.4pJ$. This is about ~ 1.3 times less than the pulse energy required to change coupling states in a recently reported work by previous researcher.

Chapter 4: *All-optical logic gates based on SPTMI coupler*- Chapter four deals with the applications of the SPTMI waveguide coupler for implementation of optically controlled logic gates. By using the basic SPTMI waveguide coupler, we have shown all-optical fundamental NOT, AND and OR logic operations. The NOT gate operation is obtained by launching control signal into one of the input access waveguides and using the optical pulse energy applied at GaAsInP cladding region as input signal. For obtaining AND logic operation, optical power launched into one of the access waveguide is used as first logic input and optical pulse energy applied to cladding is used as the second logic input. The OR logic operation is obtained by using the optical power incident into one of the access waveguides as control signal and power into the other access waveguide as one input signal and applying optical pulse energy into the cladding as the second input signal. Selection of logic operation is made by the ON and OFF states of the control signal applied.

Total length of the SPTMI waveguide coupler for fundamental logic gate operations is obtained as $\sim 142.29\mu m$. This device length for NOT, AND and OR logic operations is found to be about ~ 5.9 times compact than a recent work realizing NOT and AND logic operations. Moreover, the optical pulse energy required for switching of logic states is found to be $16.4pJ$, which is about ~ 1.65 times less than the recent work reported previously.

In this chapter, we have also proposed new structure for universal gates by cascading two stages of couplers and demonstrated simultaneous NAND and NOR logic operation with same structure by considering proper control signals. Using the same cascaded structure, the XOR logic gate has also been demonstrated by selection of proper control and input signals.

Chapter 5: *Optically controlled, tunable power splitter based on SPTMI waveguide coupler* - Chapter five introduces an optically tunable, compact power splitter using the basic SPTMI waveguide coupler. Using a 1×2 SPTMI waveguide coupler, a 3dB power splitter is designed with a device length of $\sim 143.79\mu m$. Index modulation of the cladding region due to applied optical pulse results in an additional phase change between the excited SPP modes propagating through the silicon core. This leads to a variation in the normalized output power at the output access waveguides and hence, a variation in the optical power splitting ratio. Thus, the power splitting ratio of the 3dB optical power splitter can be controlled optically, by varying the energy of optical pulse applied at GaAsInP cladding.

The splitting ratio of the 3dB optical power splitter can be tuned dynamically in a wide range from 50% : 50% to 1% : 99% and from 50% : 50% to 99% : 1% by varying the energy of applied optical pulse between $0pJ - 8pJ$. The proposed 3dB tunable optical power splitter is found to be about $\sim$ 1.4 times compact than a previous work on variable optical power splitter, reported recently. The proposed device is free from some major limitations seen in previous works such as narrow tuning range, selective splitting ratio and the need of manual tuning.

Chapter 6: *Conclusion and future scope*- This chapter concludes the thesis by summarizing the basic contributions made in the thesis. The contributions discussed in chapter 3, chapter 4 and chapter 5 in the thesis are summarized in this chapter. Some future directions for further research in this area are also suggested in this chapter.