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VLSI Photonics: Science and Engineering of Micro/Nano-scale High-Density Photonic Integration

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***Absract*-This paper presents an overview of our work on the theory, design, fabrication, and integration of micro/nano-scale optical devices as applicable for all-optical generic and application-specific VLSI photonic integration. The micro/nano-optical devices are designed to perform the functions of collecting, storing, transporting, processing, switching, routing, and distributing optical signals on chips. The integrated optical components include micro/nano-scale optical waveguides, switches, modulators, sensors, directional couplers, multi-mode interference devices, micro-ring resonators, photonic crystal devices, and plasmonic devices made of polymer, silicon and semiconductor materials. The paper discusses scientific and engineering issues of miniaturizing and integrating micro/nano-scale photonic devices of small and ultra-small dimensions to a very large scale integration density as applicable for specific functions. Scientific and engineering issues are examined and examples of progresses are presented.**

Keywords: microphotonics, nanophotonics, photonic integration, photonic circuits

I. INTRODUCTION

In the 20th century, electrical circuits based on copper wires and electrical/electronic devices affected the information technology by way of what we now know as electrical printed circuit boards (PCBs) and VLSI integrated circuits. Here, in a similar manner, we extended this concept to the domain of optics and photonics and performed a systematic study on the science and engineering of high-density integration of micro/nano-scale optical circuits and devices as applicable for optical printed circuit board (O-PCBs) and VLSI photonic circuits.

This paper presents an overview of our collective work on the theory, design, fabrication, and high-density integration of the micro/nano-scale optical circuits and devices that we have developed in the form of O-PCBs and VLSI photonic circuits. Micro/nano-photonic wires and devices are interconnected and integrated on a chip to form micro/nano-circuits of various functions that are compact, high-speed, intelligent, light-weight, low-energy and environmentally friendly, low-cost, and high-volume applications. Photonic devices include micro/nano-scale lasers, switches, couplers, detectors, sensors, actuators, modulators, and related devices to perform the functions of sensing, storing, transporting, processing, switching, routing and distributing optical signals on flat modular boards or substrates, as applicable for datacom, telecom, transportation, aero-space, avionics, bio/medical, sensor, and environmental systems. The PCBs are designed to overcome the limitations of the electrical PCBs and the VLSI photonic systems are designed to overcome the limitations of the VLSI electrical systems. They are also designed to provide diverse functions by integrating convergent IT/BT/NT micro/nano-devices and circuits.

We examine the scientific and engineering issues and challenges relating to the interconnecting two different photonic devices of different shapes, sizes, materials, and physical characteristics, regarding miniaturization, interconnection and integration of micro/nano-scale photonic devices, circuits, and networks leading to ultra-small and very large scale integration and discuss their potential applications mentioned above. The issues include the compatibility issues between micro/nano-devices such as materials mismatch, size mismatch, mode mismatch, optical mismatch, power mismatch, and mechanical/thermal mismatch. Some of the recent examples are examined.

II. SCIENTIFIC AND ENGINEERING ISSUES FOR MICRO/NANO-SCALE INTEGRATION

The scientific and technological issues of interconnection and integration include diverse compatibility issues between micro/nano-devices of diverse nature, such as materials mismatch, size mismatch, shape mismatch, mode mismatch, optical mismatch, and mechanical/thermal mismatches. The paper examines these mismatches between various couples of devices: For example, the mismatches between the cylindrical optical fibers and rectangular polymer waveguides; between polymer waveguides and silicon waveguides; between rectangular polymer/silicon waveguides and photonic crystal waveguides/devices; between rectangular polymer/silicon waveguides and silicon nanowires; between rectangular polymer/silicon waveguides and plasmonic wires/devices; and between plasmonic wires/devices and various nano-scale photonic, electronic, or bio devices.

III. EXAMPLES OF MICRO/NANO-PHOTONIC INTEGRATION

As an example, we examine the nano-scale integration between dielectric nano-wires and plasmonic wires. First, we investigate the lightwave propagation characteristics along the nano-wires and explain them in terms of plasmon waves propagating along the surfaces of the nano-wires. We analyze the propagation characteristics of the slow plasmonic lightwave and the fast lightwaves. Based on these analyses, we design the integrated structure of coupled structure between the dielectric nano-wires and plasmonic wires and examine the optical mismatch problem between the two wires for VLSI nano-photonic circuit applications. The plasmonic waveguide devices are integrated with other micro/nano-scale photonic devices, either on a board on a chip.

We also analyzed the effective index of the silicon waveguide and the SPP waveguide and designed a guided directional coupler based on the matching of the effective refractive indices between two waveguides, using 3-D finite element method. We calculated the mode field of the individual silicon nano-waveguide and the SPP nano-waveguide. We then calculated the coupled eigen-modes of even and odd eigen-modes directly to analyze the coupling between two nano-waveguides. For the even mode, the magnetic field has the same direction in all the position while the odd mode has opposite field direction on the two nano-waveguides. In terms of energy transfer, we find that the lightwave coming into silicon wire is transferred to the SPP wire due to the refractive index matching or the optical impedance matching. The modes of both single and slot SPP waveguide are excited by the electrical filed component normal to metal-dielectric interface. An infinitely wide structure supports only two purely bound transverse magnetic modes that exhibit symmetry and asymmetry modes. Unlike the structure with infinite width, the pure TM modes are not supported by a thin metal strip. All six filed components are present in all modes. The modes are excited by two polarizations, transverse electric mode and transverse magnetic mode in the case of 3-dimensional geometry with finite width and finite height. For a single SPP waveguide we find that the SPP modes are not excited by TE mode but by TM mode in the lateral guided wave coupler. The TE mode also has the electrical field component normal to metal-dielectric interface. However, TE mode cannot excite the SPP mode by the guided wave coupler in lateral direction. In the slot SPP waveguide, we find that the SPP modes are not excited by TM mode but by TE mode in the lateral guided wave coupler.

We also used surface plasmon-polaritons (SPPs) formed on a flat metal surface like silver or gold for micro/nano-photonic circuits and networks. We have designed and fabricated stripe waveguides, horizontal directional couplers, vertically integrated directional couplers, using plasmonic waveguides. Some of the photonic crystal based nano-scale networks that we have achieved include: power-splitting devices using 2-dimensional photonic crystal directional couplers; self-collimating super-prism device; photonic crystal wavelength-splitter; a two-dimensional passive optical network triplexer; and others. We also examined the input coupling efficiencies and output coupling efficiencies of various interface structures between a rectangle polymer/silicon waveguide and photonic crystal waveguides/device.

In the use of photonic crystals, we have designed and fabricated ultra-small cavity light sources, surface emitting band-edge lasers, directional couplers, multimode interference (MMI) devices, position-dependent wavelength splitters, triplexers, modulators, and switches. We have been able to couple the light in and out of surface emitting photonic crystal band-edge lasers, for example, by using optical fiber end coupling. We will also couple the light in and out of the photonic crystal lasers by way of waveguides.

In the use of nano-wires for photonic integration, we have been able to use design and fabricate silicon nano-wires down to several hundred nanometer thickness and couple them with the photonic crystal nano-waveguides. We also successfully demonstrated position-dependent light output coupling by way of size-controlled photonic crystal defect cavities positioned along the photonic crystal waveguides. We also have been able to successfully couple the light from nano-wire CdS light-emitting devices (LEDs) or nano-wire GaN LEDs into the photonic crystal nano-waveguides.

IV. SUMMARY AND CONCLUSION

We have proposed the concept of VLSI photonics and have shown some examples of micro/nano-scale integration of micro/nano-photonic wires and devices, and discussed scientific and engineering issues and solutions thereof for its progress.

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