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All-Optical QPSK Label Recognition in Photonic Switching Networks using MMIs on the Silicon-on-Insulator (SOI) Platform

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Abstract **– We present a new photonic circuit based on multimode interference (MMI) structures for the recognition of Quadrature Phase Shift Keying (QPSK) coded labels in optical switching networks. The proposed photonic circuits use only 1x2, 4x4 and 2x2 cascaded MMIs. The performance of these devices is rigorously analyzed and validated using the finite-difference beam propagation (BPM) and Eigenmode Expansion (EME) method. The proposed structure is designed using the silicon on insulator (SOI) platform, which is compatible with the existing CMOS technology. By using the MMIs, the new proposed design has advantages of low loss, compactness, high bandwidth and large fabrication tolerance compared to the recent research published in the literature based on X-junction couplers and directional couplers. The fabrication tolerance for the MMI length is ±100 nm and the bandwidth is about 15nm.**

Index Terms- QPSK modulation, Multimode interference (MMI), integrated optics, silicon photonics, and label recognition.

INTRODUCTION

Header processing stands out as a crucial function in the prospective development of optical packet networks. Various architectural solutions have been devised to carry out this task, with optical correlators and all-optical logic gates emerging as prominent approaches. Optical correlators exhibit commendable performance in terms of quality, but they necessitate opto-electronic (O/E) conversions to handle signals, employing electronic circuitry for simultaneous processing of multiple bits. Unfortunately, these O/E conversions pose a drawback, particularly when aiming for high-bit-rate operations, making architectures employing them less suitable, even at bit rates around 40 Gbit/s.

In contrast, all-optical logic gates offer a more favorable alternative as they can be fully implemented within the optical domain, eliminating the need for O/E conversions.

The integration of optical signal processing into routing nodes within high-speed photonic networks is anticipated [1]. In current optical network switching nodes, the processing speed of optical packets primarily depends on electrical processing. However, the bottleneck in achieving high-speed networking lies in optoelectric and electrooptic conversion, followed by subsequent electrical processing [2]. To overcome this limitation and achieve high-speed and broadband photonic networks, there is an increasing preference for ultrafast optical processing without the necessity for converting signals to electricity.

The application of optical signal processing is envisioned for integration into routing nodes within high-speed photonic networks [1]. Within the switching nodes of current optical networks, the speed of processing optical packets predominantly relies on electrical processing. However, the optoelectric and electrooptic conversion, along with subsequent electrical processing, represent a bottleneck in achieving high-speed networking [2]. To address this limitation and realize high-speed and broadband photonic networks, there is a growing preference for ultrafast optical processing without the need for conversion to electric signals.

In the domain of optical processing, the crucial role of recognizing optical labels is highlighted as a key function in photonic label switching networks [3]. Various approaches to encode and decode optical labels have been investigated.

Particularly noteworthy among these methods is the use of the phase of coherent light, which has demonstrated effectiveness in diverse systems. The interference between multiple signals can be exploited in certain methods to transform the phase information of the signal into its intensity.

In the context of optical communication, where optical time-series pulse trains are used to encode different labels, the use of optical correlators becomes essential [4]. These correlators are tasked with comparing these pulse trains against pre-stored codes to identify matching labels. A notable challenge in many systems is that each correlator is typically engineered to recognize only a single specific label. This leads to a requirement for multiple correlators at each network node, enabling the recognition and processing of information associated with various labels.

Recent advancements have revealed waveguide-type circuits that include arrayed waveguide gratings (AWG), offering the capability to process multiple labels using a single device. Building on our prior research, we have developed a waveguide-type circuit capable of distinguishing codes formatted in Quadrature Phase Shift Keying (QPSK). In this system, a unique identifying pulse is routed to a specific destination output port, which correlates with the code's label. This method's adaptability is enhanced by the integration of QPSK, which allows for a broader range of code representations [5]. While the utilization of QPSK signals in optical circuits is not new, having been previously investigated in the realm of communication system receivers, the incorporation of QPSK labels into label routing systems introduces a need for specialized optical processing techniques.

This research introduces a novel MMI based circuit designed to identify Quadrature Phase Shift Keying (QPSK) labels. The core mechanism of our approach is based on the self-routing of an identifying pulse within the circuit. Initially, we outline the design of an optical circuit module specifically tailored to detect the optical phase of a QPSK input signal, which is capable of recognizing a single QPSK bit pulse. For handling QPSK codes that consist of multiple bits, we extend the recognition capability by linking several of these basic modules in a tree-like structure. This is facilitated through a phase adjustment circuit, allowing for comprehensive recognition of complex QPSK codes. The process presupposes that the QPSK coded labels are preprocessed to convert from serial to parallel format. Once in parallel form, the pulses are then fed into our specially designed recognition circuit [6]. The architecture of the circuit for n-bit QPSK labels includes both input and output ports, featuring an additional input port specifically for the identifying bit. For instance, a circuit handling a two-bit QPSK code would be equipped with three input ports and 16 output ports. To demonstrate the effectiveness and processing accuracy of this basic module, we conduct simulations using the finite-difference beam propagation method (FD-BPM).

These simulations are crucial in validating the operational capabilities and efficiency of our proposed optical circuit in recognizing QPSK labels.

This study presents an innovative label recognition system specifically designed for labels coded with Quadrature Phase Shift Keying (QPSK). The core functionality of this system is realized through the use of optical integrated circuits. To validate and thoroughly understand the efficacy of this label recognition approach, two key simulation methods were employed: the finite-difference beam propagation method (BPM) and Eigenmode Expansion (EME). These simulation techniques provide a detailed and accurate analysis of the system's performance, ensuring the reliability and effectiveness of the proposed QPSK label recognition structure.

PROPOSAL OF THE NEW ARCHITECTURE

In the exploration of representing routing label information with optical signals, several methodologies have been studied, such as coding in the time domain, spectral domain, and hybrids of these techniques. Specifically, this research concentrates on utilizing time-sequential coded pulse trains employing the QPSK (Quadrature Phase Shift Keying) modulation format. A critical aspect of this approach is ensuring the accurate identification of the absolute phase of the signals. To achieve this, a reference signal is strategically placed before the pulse train that denotes an address. This reference signal serves as a benchmark for phase comparison. For a label encoded with (N + 1) symbols in this format, the electric field of the optical pulse train is characterized in a specific mathematical expression. This formulation is critical as it lays the foundation for how the optical signals are structured and interpreted within the system, ensuring that each unique label can be precisely identified and processed according to its designated routing information.The electric field of the optical pulse train for a label with (N + 1) symbols is expressed as follows [2]:

$$E_{label}(t) = \sum_{i=0}^{N} a_i f_0(t - i\Delta t) \exp(j\varphi_i) \exp(j\omega(t - i\Delta t)) \tag{1}$$

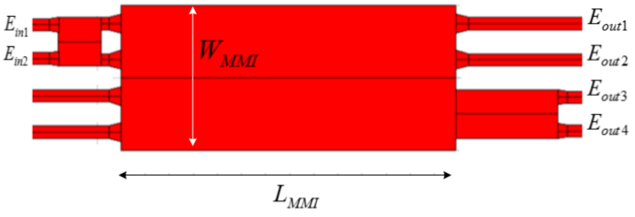
Where, the term $f_0(t)$ represents the envelope of a pulse characterized by the angular frequency ω, amplitude a_i, phase φ_i, and the pulse period Δt. This mathematical representation encapsulates the essential properties of the pulse in the time sequential coded pulse train.

In our study, we have developed an innovative design for an optical label recognition circuit using Quadrature Phase Shift Keying (QPSK), tailored specifically for the Silicon-on-Insulator (SOI) platform. The cornerstone of this design is the new Phase Recognition Circuit (QPRC), which utilizes Multimode Interference (MMI) couplers.

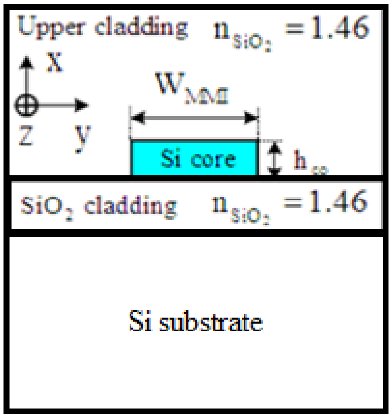
These couplers are arranged in a cascading fashion as part of the proposed structure, a layout of which is illustrated in Fig. 1(a). The SOI waveguide, a key component in this design, has specific dimensions: it is 220 nm in height and 500 nm in width. This waveguide operates as a single-mode waveguide at a wavelength of approximately 1550 nm. To provide a comprehensive understanding of the design, Fig. 1(b) presents a cross-sectional view of the device. Additionally, Fig. 1(c) illustrates the profile of the optical field within the waveguide. These visual representations are crucial for understanding the physical layout and the optical behavior of the QPRC within the SOI platform.

Figure 2 in the referenced study showcases the design of a fundamental circuit module, which is engineered to identify the phase of an incoming Quadrature Phase Shift Keying (QPSK) code [7]. This Phase Recognition Circuit (QPRC) is structured with two input ports and four output ports.The study then shifts focus to the recognition of optical labels that are represented by a train of multiple pulses. In this configuration, as shown in Fig. 2(a), the first bit of the pulse train is designated as the ID bit. This ID bit acts as a reference pulse signal, aiding in the recognition process. An important aspect of this system is that the phase relationship between the pulses in the train is maintained, which eliminates the need for generating a separate reference bit signal at the router.

To efficiently handle the time-serial pulses, the system incorporates a serial-to-parallel converter. This converter serves as a preprocessing unit, allowing for easier and more effective recognition of the pulses. The functionality and layout of this converter are detailed in Fig. 2(b). This setup ensures that each pulse in the train can be accurately and reliably recognized, which is crucial for the effective processing of QPSK coded optical labels.



(a)



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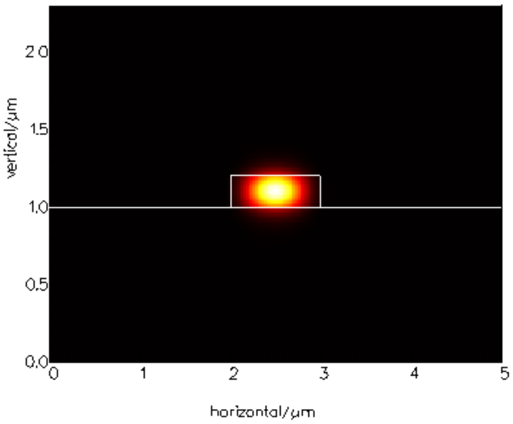
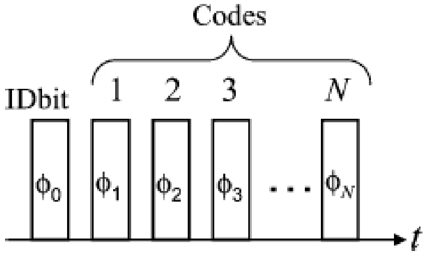
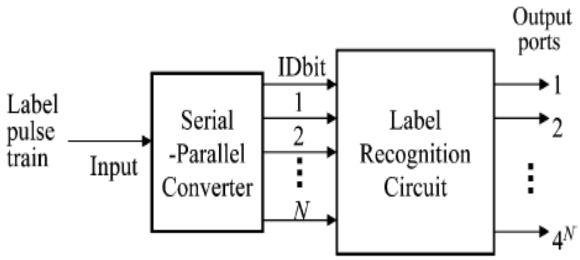


(c)

Fig 1. Optical structure based on MMIs for QPRC (a) circuit, (b) cross-sectional view and (c) field profile



(a)



(b)

Fig 2. Principle of QPSK label recognition [7]

In our initial analysis, we focus on the recognition of two-bit codes using the proposed optical circuit. The label recognition system for these two-bit codes consists of a two-stage configuration of Quadrature Phase Recognition Circuit (QPRC) modules. These modules are arranged in a tree structure, as demonstrated in Fig. 3. In this setup, the ID bit pulse and the first bit pulse of the code are fed into input ports 1 and 2, respectively, of the first-stage QPRC module. Following the processing in this module, its four outputs are then routed to input port 1 of each of the second-stage QPRC modules. Concurrently, the second-bit pulse of the code is subjected to a fourfold amplification. This amplified signal is then split into four separate pulses. Each of these pulses is directed to input port 2 of the second-stage QPRC modules. This particular arrangement and processing methodology allow for the effective and systematic recognition of two-bit codes. By employing a staged approach, where each stage is responsible for processing different bits of the code, the system can accurately decipher the two-bit QPSK labels. The tree structure of the QPRC modules ensures that all possible combinations of the two-bit code are accounted for and correctly identified. By carefully selecting the locations of the input and output waveguides at [8]

$$x_i = (i + 0.5)\frac{W_{MMI}}{4} \tag{2}$$

The 4x4 MMI coupler at a length of $L_1 = \frac{3L_\pi}{2}$ is described by the following transfer matrix:

$$M = \frac{1}{2}\begin{bmatrix} 1-j & 0 & 0 & 1+j \\ 0 & 1-j & 1+j & 0 \\ 0 & 1+j & 1-j & 0 \\ 1+j & 0 & 0 & 1-j \end{bmatrix} \tag{3}$$

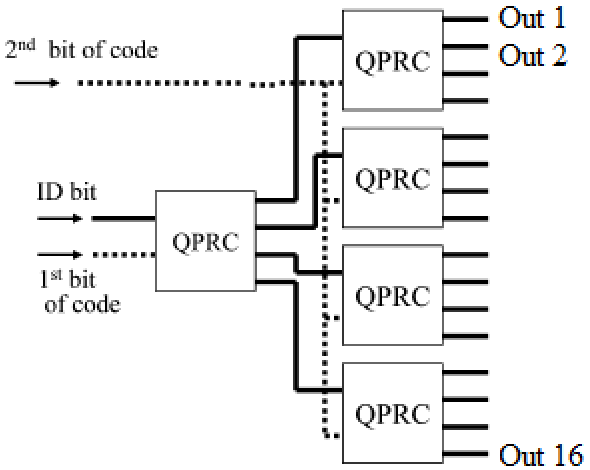


Fig 3. QPSK label recognition by interconnecting the

The processing sequence in the optical circuit for recognizing two-bit QPSK codes unfolds as follows: Initially, the ID bit pulse and the first bit pulse of the code are introduced into input ports 1 and 2 of the first-stage Quadrature Phase Rotation Circuit (QPRC) module, respectively. After these pulses are processed, the outputs from this first-stage QPRC are routed to input port 1 of each module in the second-stage of QPRCs. Simultaneously, the second-bit pulse of the code is subjected to a process of fourfold amplification. This amplified signal is then split into four separate pulses. Each of these divided pulses is fed into input port 2 of the four individual second-stage QPRC modules. To maintain accuracy and consistency in the processing within the second-stage QPRC modules, it's crucial that the phase of the output signals from the first-stage QPRC is precisely replicated. This step ensures that the phase relationship is preserved throughout the processing stages, which is vital for the accurate recognition and interpretation of the two-bit QPSK codes.

In the proposed optical circuit, the cascaded Multimode Interference (MMI) couplers play a pivotal role in identifying the phase of the incident wave encoded in the QPSK format. The strategic implementation of these MMI couplers in a cascaded connection forms the backbone of the system, enabling it to effectively discern and process two-bit addresses. One of the most critical aspects of this cascading MMI setup is the relationship between the input and output fields. This relationship is key to how the circuit interprets and processes the incoming optical signals. The complex amplitudes of the signals at the output ports of the MMI couplers are of particular interest.

These amplitudes can be mathematically formulated to represent how the input signal, coded in QPSK format, is transformed as it passes through the MMI couplers. This mathematical representation of the complex amplitudes is essential as it provides a detailed understanding of the signal processing occurring within the circuit. It allows for the prediction and analysis of how different input signals (phases) will be represented at the output, thereby enabling the precise recognition of the QPSK-encoded two-bit addresses by the system.

The complex amplitudes of the output signals at the output ports can be expressed by:

$$\begin{pmatrix} E_{out1} \\ E_{out2} \\ E_{out3} \\ E_{out4} \end{pmatrix} = \frac{1}{2}\begin{pmatrix} 1 & \exp(j\frac{3\pi}{2}) \\ \exp(j\frac{7\pi}{4}) & \exp(j\frac{7\pi}{4}) \\ \exp(j\frac{5\pi}{4}) & \exp(j\frac{\pi}{4}) \\ \exp(j\frac{3\pi}{2}) & 1 \end{pmatrix}\begin{pmatrix} E_{in1} \\ E_{in2} \end{pmatrix} \quad (6)$$

SIMULATION RESULTS AND DISCUSSIONS

To initiate the development of the QPRC (Quadrature Phase Recognition Circuit) circuits on the Silicon-on-Insulator (SOI) platform, a crucial step is the design optimization. This process begins with the sizing of the Multimode Interference (MMI) couplers, a key component of the QPRC. Through beam propagation method (BPM) simulations, we have optimized the MMI width to be 6 µm. This dimension is chosen to ensure the MMI coupler is both compact and offers high performance. Further, the impact of the MMI length on the overall device performance is carefully examined. This examination involves assessing parameters like excess loss and the balance in a 4x4 MMI coupler. These assessments are critical in understanding how changes in the MMI dimensions affect the circuit's functionality and efficiency.

Our simulations have led to an encouraging finding regarding the fabrication tolerance of the MMI coupler [9]. Specifically, we've determined that the MMI length can tolerate variations of ±100 nm while maintaining a normalized output power variation of just 0.01. This level of fabrication tolerance is significant as it falls within the capabilities of current lithographic techniques, such as electron beam (e-beam) lithography or 193 nm deep ultraviolet (UV) lithography.

This tolerance level indicates that the MMI couplers can be fabricated with a high degree of precision and reliability, which is essential for the successful implementation and operation of the QPRC circuits in optical communication systems. The ability to maintain consistent performance despite minor variations in fabrication underscores the robustness and practicality of the proposed design for real-world applications.

The results from our Beam Propagation Method (BPM) simulations provide valuable insights into the performance characteristics of the Multimode Interference (MMI) coupler, particularly in terms of its bandwidth and wavelength response. According to the simulations, the MMI coupler exhibits a -1dB bandwidth that extends across a 35nm range, specifically from 1532nm to 1567nm [10]. This bandwidth indicates the range over which the MMI coupler effectively operates with minimal signal loss. Furthermore, within a narrower wavelength span of 15nm centered around the operational wavelength of 1550nm, the simulations reveal an important aspect of the MMI coupler's performance. It shows that the normalized output powers at the first and fourth output ports of the MMI coupler are in close alignment with the ideal 50:50 split ratio. This observation is critical as it demonstrates the coupler's capability to maintain a balanced output, which is a key requirement for efficient signal processing in optical circuits. This analysis not only confirms the MMI coupler's operational efficiency within a targeted wavelength range but also highlights its robustness in maintaining desired output characteristics under varying wavelength conditions. Such insights are crucial for understanding the device's applicability and reliability in practical optical communication systems, where consistent performance across different wavelengths is essential.

The Beam Propagation Method (BPM) simulations conducted in our study reveal significant results regarding the behavior of a two-bit QPSK optical pulse train within the system. When this pulse train is introduced into the circuit, the simulations allow us to observe the resulting normalized intensity of these pulse trains as they emerge from the system.

Specifically, the outcomes are illustrated in Fig. 4 of our study. This figure displays how the intensity of the optical pulses is distributed across the four output ports of the circuit. The visualization in Fig. 4 is crucial as it provides a clear representation of how the optical pulse train, encoded in the two-bit QPSK format, is processed and divided within the circuit. The ability to track and analyze the intensity distribution of the pulse train at the output ports is essential for understanding the effectiveness of the circuit in processing and recognizing QPSK signals. It allows for an assessment of how well the circuit maintains the integrity of the signal and the fidelity of the information it carries, which are key factors in evaluating the performance of the optical QPSK label recognition system.

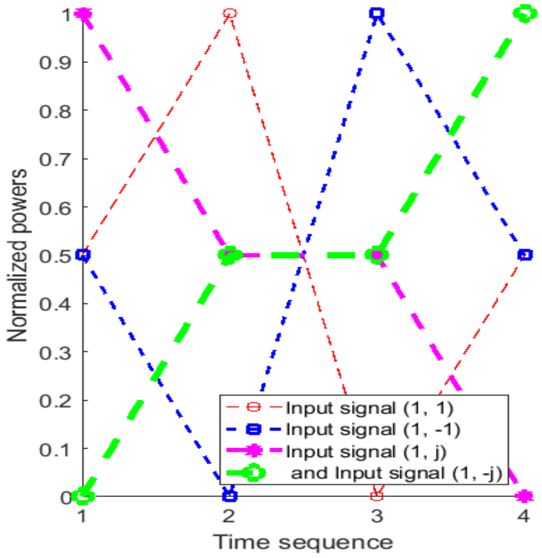


Fig. 4 BPM simulations for normalized powers at output ports 1, 2, 3 and 4

Utilizing the Beam Propagation Method (BPM) simulation, we are able to present a comprehensive visualization of how the fields propagate through the entire device. This detailed representation is showcased in Fig. 5 of our study. The BPM simulation is instrumental in illustrating the behavior of the optical fields as they move through the various components of the circuit. The simulation results are particularly noteworthy because they demonstrate a strong correlation with the numerical simulations that were conducted. This agreement between the BPM simulation results and the numerical simulations is significant. It indicates that the theoretical models and assumptions made during the design phase are accurately reflected in the simulated behavior of the optical fields within the device. This congruence is crucial for validating the design and functionality of the optical device. It instills confidence that the device will perform as expected in real-world applications, based on the simulated behavior. The ability to predict and visualize the field propagation within the device aids in fine-tuning the design and can also guide future enhancements or modifications.

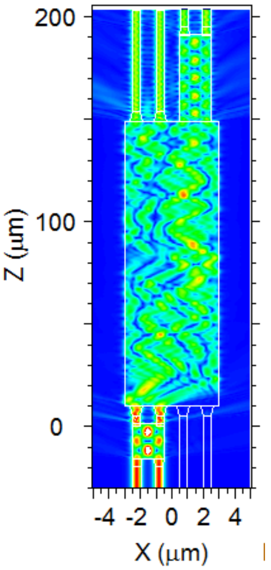


Fig. 5 BPM simulations for input signal at port 1 and 2

CONCLUSION

In our research, we have introduced a groundbreaking optical circuit that utilizes multimode interference (MMI) structures, specifically designed for the recognition of labels encoded using Quadrature Phase Shift Keying (QPSK). This is the first instance of such a circuit being presented. The key feature of our design is the use of cascaded MMI structures, which form the core of the label recognition system. Our newly proposed design offers several significant advantages over recent designs that are based on X-junction couplers, as found in contemporary literature. These advantages include: (1) Low Loss: the circuit is designed to minimize signal loss, ensuring efficient transmission and processing of optical signals. (2) Compactness: The MMI-based design allows for a more compact circuit, which is beneficial in applications where space is a constraint. (3) High Bandwidth: With a bandwidth of about 15nm, the circuit is capable of handling a wide range of frequencies, making it versatile for various optical communication needs. (4) Large Fabrication Tolerance: One of the notable features of this design is its large fabrication tolerance, particularly in the MMI length, which is ±100 nm. This level of tolerance makes the circuit more forgiving to minor fabrication inaccuracies, thereby simplifying the manufacturing process.

The proposed sensor structure, thanks to its compactness and efficiency, is well-suited for integration with all-optical label switching networks. This integration potential enhances the applicability of our design in advanced optical communication systems, where reliability, efficiency, and precision are paramount. The combination of these features makes our MMI-based QPSK label recognition circuit a promising development in the field of optical communications.

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