Multi-Transverse Mode Multiply-and-Accumulate Operation toward Advancement of Photonic Accelerators

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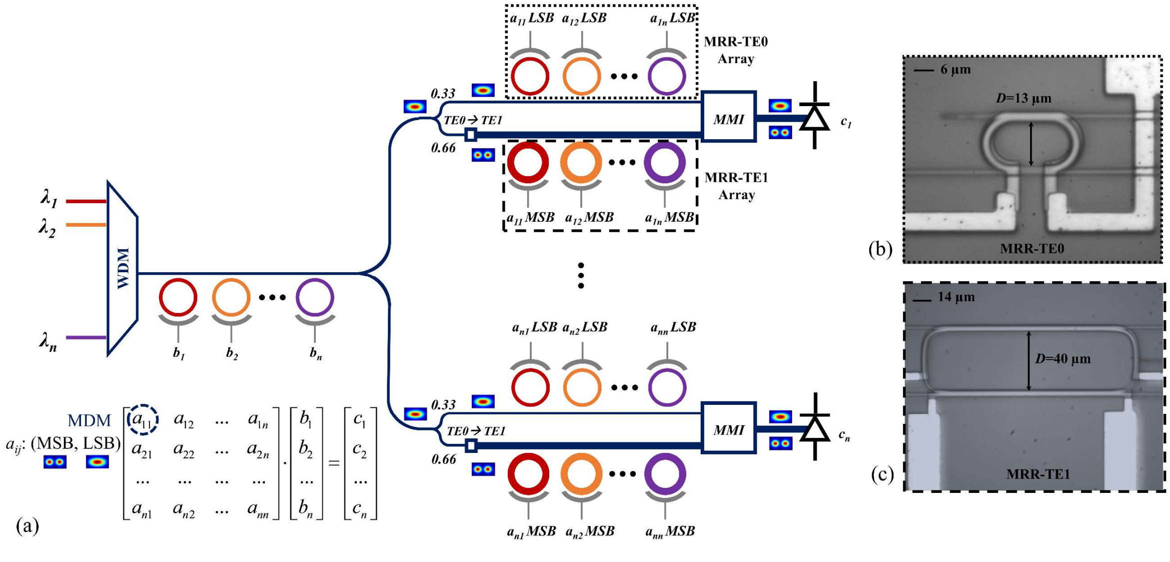
Abstract: We demonstrate a novel mode-division-multiplexing subsystem achieving four output power levels using two single-bit rings on two TE modes for photonic accelerators. The photodetector combines the energy of two TE modes without requiring coherent summation. © 2024 The Authors

1. Introduction

Photonic accelerators potentially provide promising solutions to the ever-increasing compute-resource intensive processing demands. Multiply-and-accumulate (MAC) operation, as a cornerstone of these processing tasks, was demonstrated in the optical domain using microring resonator (MRR) weight banks [1]. The weighting operation is attained by tuning the MRRs in and out of resonance and, hence intensity modulating the signal at a certain wavelength accordingly, while an intensity modulated array of WDM signals ($\lambda_1 : \lambda_n$) prepares the input vector for the multiplication (dot product) operation. A photodetector incoherently accumulates the weighted optical signal completing the MAC operation.

Due to the MRRs susceptibility to thermal fluctuations and presence of inter-channel crosstalk in such WDM system, attaining a reasonable weight resolution remains challenging. A state-of-the-art weight resolution of nine bits is demonstrated with a dithering control scheme that dynamically tune the weights against different sources of drifting errors [2]. Although photonic accelerators are desired to achieve a comparable computational resolution with their electronic counterparts, improving the weight resolution deals with two major challenges: 1) higher weight accuracy is only achievable at the cost of increased power consumption of the control circuitry, which deteriorates the overall energy efficiency of the system; 2) the resonance extinction ratio is inherently finite; MRRs with higher resonance quality factor not only demands for more complex and power-hungry control circuitry but also slows down the system due to larger photon lifetime within the resonator. In this study, we propose deploying the fundamental and first-order transverse-electric modes (TE0, TE1) in two optical paths to be weighted with MRRs, and incoherently accumulated by a photodetector. We experimentally demonstrate realizing multi-transverse mode MAC operation by using MRR-



$$\begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \dots & \dots & \dots & \dots \\ a_{n1} & a_{n2} & \dots & a_{nn} \end{bmatrix} \cdot \begin{bmatrix} b_1 \\ b_2 \\ \dots \\ b_n \end{bmatrix} = \begin{bmatrix} c_1 \\ c_2 \\ \dots \\ c_n \end{bmatrix}$$

Fig. 1. (a) Architecture diagram of the proposed MRR-based photonic accelerator enabled with both WDM and MDM technologies for realizing MAC operations. Both multi-transverse and fundamental mode MRRs are deployed to implement the MSB (MRR-TE1) and LSB (MRR-TE0) of each weight, respectively. The constituent MDM building blocks are described in the text; (b, c) Micrographs of both MRR-TE0 (b), and MRR-TE1 (c) in the fabricated SOI chip.

TE0, and MRR-TE1 with single-bit resolution control to attain four distinct output power levels. This architecture mitigates the weight control circuitry complexity to a single-bit resolution. Measured modal crosstalk levels of approximately -12 dB within the wavelength range of [1530:1550] nm offers potential scalability of this architecture to higher-order modes for increasing the number of resolved output power levels toward realizing a more accurate MAC operation.

2. Principles of the proposed MAC architecture

As an alleviating solution to the aforementioned challenges for increasing the computational resolution of MRR-based photonic accelerators, we propose exploiting mode-division-multiplexing (MDM) technology to resolve more output power levels using a set of additional MRRs resonating at the first higher-order transverse mode (TE1) as demonstrated in Fig. 1 (a). This mode is excited from the fundamental mode (TE0) by a mode converter. Each of the weight matrix elements (a_{ij}) are realized with a set of two MRRs coupled to the TE0 and TE1 signal paths bearing an input optical power with the ratio of 0.33:0.66. The weighted TE0 and TE1 signals are fed to a 2×1 multi-mode interferometer (MMI). Due to the orthogonality of TE0 and TE1 optical signals, they are both superposed incoherently to the MMI output path without any prior phase matching requirements. The optical signal path ends up directly at the photodetector, inherently mode insensitive, and thus accumulating both weighted TE0 and weighted TE1 signals to complete a multi-transverse mode MAC operation.

For a specific wavelength and a single-bit resolution weighting control for TE0 and TE1 as the least and most significant bits (LSB, MSB), respectively, four different optical power levels are achieved at the output. In this matter, the proposed architecture can relax the requirements of the weight control circuitry and potentially increase the optical output resolved power levels. Expanding this architecture by further deployment of higher-order modes (TE2, TE3) can scale up the number of distinct output power levels leading to a higher resolution MAC operation. In that case, the power splitting scheme is modified to 0.50:0.25:0.125:0.0625 for TE0-TE3 signals instead of the ratio of 0.33:0.66 shown in Fig. 1 (a).

3. Experimental Validation and Discussion

As a proof-of-concept design, the weight matrix architecture with a single pair of the MRR-TE0 and MRR-TE1 devices (Fig. 1 (b, c)) is fabricated in the silicon-on-insulation (SOI) technology platform at Applied Nanotools (ANT) foundry. The TE0/TE1 rings have a radius and coupling length of 6.5/20 µm and 10/95 µm, respectively. The resonance tunability is realized through titanium tungsten metal heaters deposited on top of the oxide cladding. The measured free spectral range (FSR) of the MRR-TE0 is 9.27 nm. The MRR-TE1 is designed based on [3] with an expected FSR of 1.69 nm well in agreement with the measured FSR of 1.71 nm. For an improved WDM performance of the next generation chip, the FSR of MRR-TE0 needs to be ideally identical to the TE1 ring FSR. The deployed mode converter [4] and MMI [5] designs are based on heritage work from our research group, which is publicly accessible in a library of MDM components [6].

Fig. 2 (a) illustrates the deployed experimental testbed to characterize the rings and validate the proof-of-concept design. An external 50:50 optical splitter and variable optical attenuator (VOA) adjusts the power levels to the 0.33/0.66 ratio with respect to the insertion loss of each optical path through the output. Due to the inaccessibility of integrated photodetectors in the fabrication foundry, the output optical signal is demultiplexed with an adiabatic coupler to the fundamental TE0 mode and measured off-chip. The normalized optical power transmission spectrum of TE0 and TE1 signals are shown in Fig. 2 (b, c), monitored with the first (PM1) and second (PM2) optical power meters, respectively. A maximum extinction ratio of more than 20 dB is achieved in the wavelength range of [1530:1550] nm for both rings. The insets of Fig. 2 (b, c) demonstrate the power transmission in the case of single mode excitation (i.e., disconnecting the other signal path from the external splitter output) enabling modal crosstalk evaluation. A worst-case modal crosstalk of approximately -12 dB is measured in the wavelength range of [1530:1550] nm for TE0 signal. However, because the resonance wavelength of both rings will be aligned in the working condition, this modal crosstalk does not decrease the extinction ratio.

In Fig. 2 (d), the resonance wavelength tunability of both rings at 1538 nm is characterized using a current source to find the resonance (‘0’ state) and off-resonance (‘1’ states) bias conditions for each ring. For the TE0 (LSB) and TE1 (MSB) rings, bias conditions of (8, 11) mA and (12.2, 16.4) mA are selected for their (‘0’, ‘1’) states, respectively. Note that a resonance wavelength locking scheme is not used in the applied current to the heaters. Deploying a more precise weight control scheme is necessary to align the resonance of both rings precisely to realize the high extinction ratio observed in the transmission spectra (Fig. 2 (b, c)). TE modes are orthogonal, allowing a photodetector (PD) to combine the optical power of two TE modes without requiring coherent summation, much like it combines different wavelengths in [1]. Ideally, we should employ an on-chip PD or couple the light out using a multimode grating coupler to a few-mode fiber [7] to an off-chip PD. However, due to the constraints of our single-etched passive SOI fabrication,

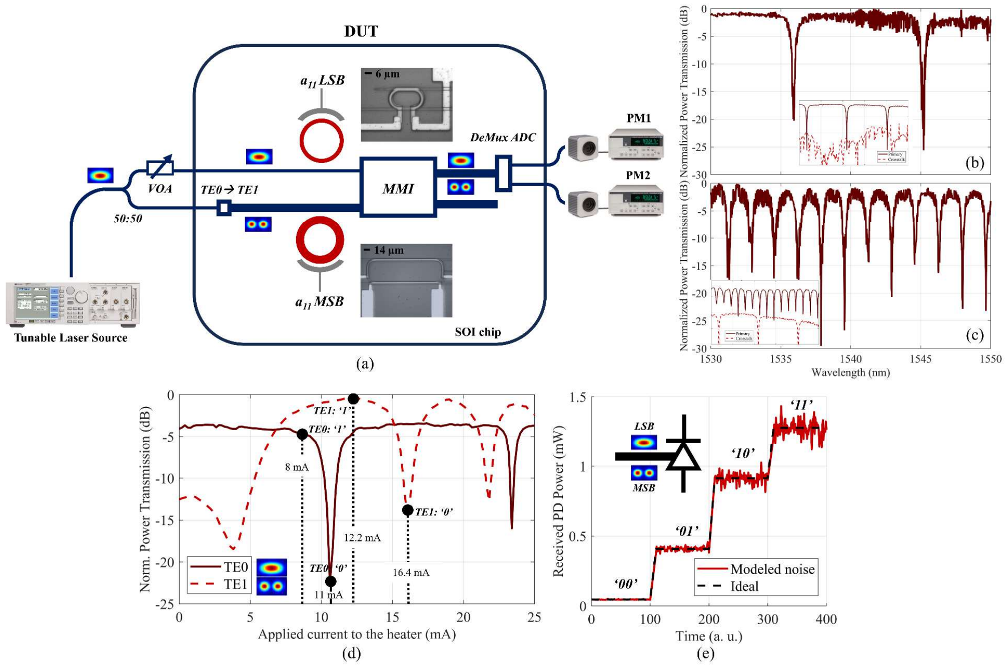


Fig. 2. (a) Experimental testbed diagram for the proof-of-concept SOI chip validation (DUT: device under test). TE1 mode excited on-chip using a mode converter (TE0→TE1) and converted back to the fundamental mode using an adiabatic mode demultiplexer (ADC); (b, c) TE0 and TE1 output power transmission spectra measured by PM1 and PM2, respectively. Insets: transmission measurement for single mode excitation for the primary (solid) and modal crosstalk (dashed) signals. (d) Tunability characterization of the DUT shown in (a) with sweeping of the applied current to the ring heaters for MRR-TE0 (LSB, solid) and MRR-TE1(MSB, dashed) at 1538 nm incident wavelength when the other ring is biased at its '0' state. (e) Theoretical optical output power levels to be received at the photodetector based on the experimental power levels. Added Gaussian noise from experimental results considered modelling MRRs output power fluctuations.

we lacked access to an on-chip PD or a multimode grating coupler. Consequently, we converted TE1 to TE0 using an adiabatic mode demultiplexer before coupling out this mode, and we employed two off-chip PDs to independently monitor the two modes and theoretically sum the power levels of the two PDs as shown in Fig. 2 (e). A random Gaussian noise is considered to model the power fluctuations observed in Fig. 2 (b, c) near the 1538 nm wavelength.

4. Conclusion

The novel integration of mode-division-multiplexing technology within microring resonator (MRR)-based photonic processors presents a significant advancement, allowing for the realization of a larger number of output power levels, while relaxing the weighting control circuitry requirement to a single-bit resolution. This assertion is substantiated by the successful implementation of a proof-of-concept design on the SOI platform, which demonstrates the feasibility of a multi-transverse mode multiply-and-accumulate operation. Notably, our experiments confirm that the superposition of two optical signal paths, corresponding to fundamental and first higher-order modes (TE0 and TE1), with single-bit weight control in two rings resonating at the same wavelength can produce four distinct power level intensities. The observed modal crosstalk of approximately -12 dB in the wavelength range of [1530:1550] nm offers the potential scalability of this novel architecture to higher-order modes leading to a more accurate MAC operation.

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