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(Article begins on next page)

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General Programmability of MZI-based Clements Mesh for Photonic Logical Operations

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***Abstract*—In this work, we examine the influence of the Coupling Layer (CL) topology on the general programmability of a 3×3 Clements mesh consisting of Mach-Zehnder Interferometers (MZIs). By adopting a hybrid optimization approach that leverages the Monte Carlo method and the Genetic Algorithm (GA), we obtain optimal phase shifts for each MZI, for each possible photonic logical operation and in every viable CL topology. Based on the Extinction Ratio (ER) metric, our programmability evaluation finds some feasible CL topologies capable of realizing over 80% of all possible truth tables with an ER value greater than 3 dB.**

***Index Terms*—Photonic programmability, Mach-Zehnder Interferometer, Coupling Layer, Clements mesh**

I. Introduction

Photonic logic gates can utilize integrated photonic components to perform logic operations, allowing for energy-efficient and ultra-fast signal processing compared with electronic counterparts [1]–[3]. Traditional photonic logic gates are normally based on optical nonlinearities such as Four-Wave Mixing (FWM) and are modulated in optical power, leading to undesirable issues including limited scalability and substantial power consumption [4]–[6].

Over the past years, Optical Inference Units (OIUs) implemented with meshes of interconnected, thermally-tuned Mach-Zehnder Interferometers (MZI) in the Clements architecture [7] have been adopted in Machine Learning (ML) applications to perform optical matrix multiplication in parallel [8]–[10]. Moreover, recent research has demonstrated the OIU capability to perform multiple linear programmable operations if a Coupling Layer (CL) is introduced to combine the matrix-vector multiplication outputs from the OIU [11].

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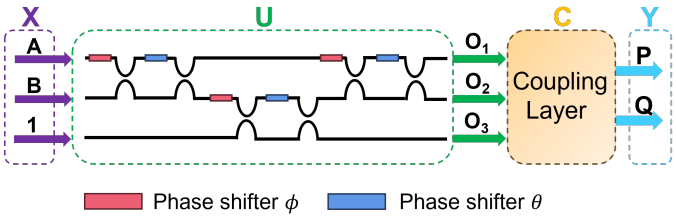


Fig. 1. Proposed structure to implement programmable photonic logical operations. The red and blue rectangles represent the two phase shifters of each MZI. X, Y represent the input and output signals of the proposed structure, respectively. U, C represent the Clements mesh and the Coupling Layer topology, respectively.

In this work, by adopting the hybrid optimization approach that combines the Monte Carlo method [12] and the Genetic Algorithm (GA) [13], we determined the optimal phase shift values for each MZI in a 3×3 Clements mesh to perform every possible photonic logical operation in each CL topology. We also studied the influence of the CL topology on the general programmability of the proposed structure, demonstrating the existence of CL topologies capable of implementing the majority of all possible truth tables, with excellent output signal quality according to the Extinction Ratio (ER) metric.

II. Proposed Structure

As illustrated in Fig. 1, the proposed structure comprises the 3×3 Clements mesh composed of MZI arrays, the CL composed of optical couplers, three input ports (A and B, while Port 3 is a constant Input Port), and two output ports (P and Q). Input Port 3 is fixed at a constant Logic "1" value so that there is always power available for the generation of photonic outputs, expanding the number of achievable photonic logical operations, particularly when both A and B

ports are assigned Logic "0" values. The CL linearly sums the matrix multiplication results from the Clements mesh and maps them to the P and Q output ports. Each MZI consists of two lossless 50% beam splitters and two phase shifters parameterized by their phases (ϕ, θ).

In the Clements mesh, the unitary transformation between channel i and the adjacent channel is formulated as follows [7]:

$$u_{i-1,i} = \begin{bmatrix} e^{j\phi_i}\cos\theta_i & -\sin\theta_i \\ e^{j\phi_i}\sin\theta_i & \cos\theta_i \end{bmatrix}; \qquad i = 2, 3. \tag{1}$$

where θ_i lies in the interval $[0, \pi/2]$, and ϕ_i lies in the interval $[0, 2\pi]$. The input logic states are encoded in the amplitude of the optical pulses.

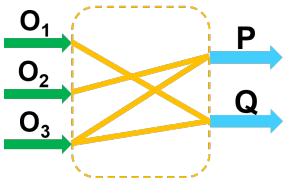
The logical relation between output Y and input X in the proposed structure is defined in [11]:

$$Y = XUC \tag{2}$$

where:

- X represents a 4×3 binary matrix (the first two columns contain all the combinations of digital inputs A and B, and the last column describes the constant input value applied to Port 3);
- Y denotes a 4×2 binary matrix where each row represents a corresponding output state;
- C is a 3×2 binary matrix with each column representing the topological connection between an output port of the Clements mesh (O_1, O_2 and O_3) and the output ports of the proposed structure (P and Q);
- U is a 3×3 unitary matrix as defined in [7].

Since not all possible C matrices correspond to useful CL topologies (e.g., trivial CL topologies for which the Clements mesh is mapped to a single output port), we set the number of viable CL topologies to 42 after excluding all trivial CL topologies. Assuming for the moment that the proposed structure is lossless, the elements of the matrix C are assigned the value 1 to represent a direct connection between the Clements mesh and the output ports (P or Q). The value $1/\sqrt{2}$ is assigned to the elements of C to account for power splitting between P and Q ports. Finally, the value 0 is assigned to the C matrix elements when no connection is present between the Clements mesh and P or Q ports. A graphical example of a CL topology and its corresponding C matrix is reported in Fig. 2.



$$C = \begin{bmatrix} 0 & 1 \\ 1 & 0 \\ 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix}$$

Fig. 2. Structure of the Coupling Layer Topology number 16.

III. Programmability Investigation

Provided that acquiring the closed-form solution of Eq. (2) is challenging due to its inherent intricacy and nonlinearity, we decide to adopt a hybrid numerical approach harnessing both the Monte Carlo method and the GA to find, for each MZI, the optimal phase shift values that satisfy the transformation mapping in Eq. (2). The optimization procedure is implemented on the MATLAB platform on a standard workstation equipped with a 12th Generation Intel® Core™ i9 processor.

First, for each viable CL topology and for every possible truth table, we run 10^6 Monte Carlo simulations by generating random phase values of all (ϕ_i, θ_i) from a uniform distribution in the input domain of Eq. (1), to obtain the initial phase shifts with minimal Mean Squared Error (MSE) as defined as follows:

$$f(\mathbf{\Psi}) = \frac{1}{8}\sum_{i=1}^{8}(P_i - Y_i)^2 \tag{3}$$

where $\mathbf{\Psi}$ is the set of phases to be configured at the phase shifters of the Clements mesh. P_i and Y_i represent the obtained output power value and the expected output power value for the i-th bit of the specified truth table, respectively.

We subsequently apply a customized GA optimization to further optimize the initial phase shift values acquired from Monte Carlo simulations. Standard hyperparameters are adopted in the GA optimizer: for example, the Population Size, the Maximum Number of Generations, and the Crossover Rate parameters are set to 10^4, 10^3, and 0.8, respectively. We also utilize the `fmincon` function from the MATLAB Optimization Toolbox to avoid possible premature convergence of the GA.

To evaluate the quality of output signals, the ER is defined as follows:

$$\text{ER(dB)} = 10\log_{10}\left(\frac{\min(P_1, Q_1)}{\max(P_0, Q_0)}\right) \tag{4}$$

where P_1 and Q_1 represent the power values of Output Logic "1" cases at P and Q ports, respectively. P_0 and Q_0 represent the power values of Output Logic "0" cases at P and Q ports, respectively.

We investigated a practical case based on the 16th CL topology whose structure is shown in Fig. 2; the P port of the selected CL topology connects to the O_2 and O_3 ports of the Clements mesh while its Q port connects to the O_1 and O_3 ports of the Clements mesh.

We tested the programmability of the case study by implementing all 256 possible user-defined Boolean function combinations at the P and Q device output ports, and found multiple Boolean operations with good ER performance.

Table I showcases one of these logical operations with good ER performance, where Port P performs an `AND` operation and Port Q performs an `OR` operation. In this example, the ER value is calculated as 5.42 dB based on Eq. (4). This value indicates a sufficiently large contrast between the power values corresponding to Output Logic "0" cases and Output Logic "1" cases, thereby facilitating robust automatic detection in the

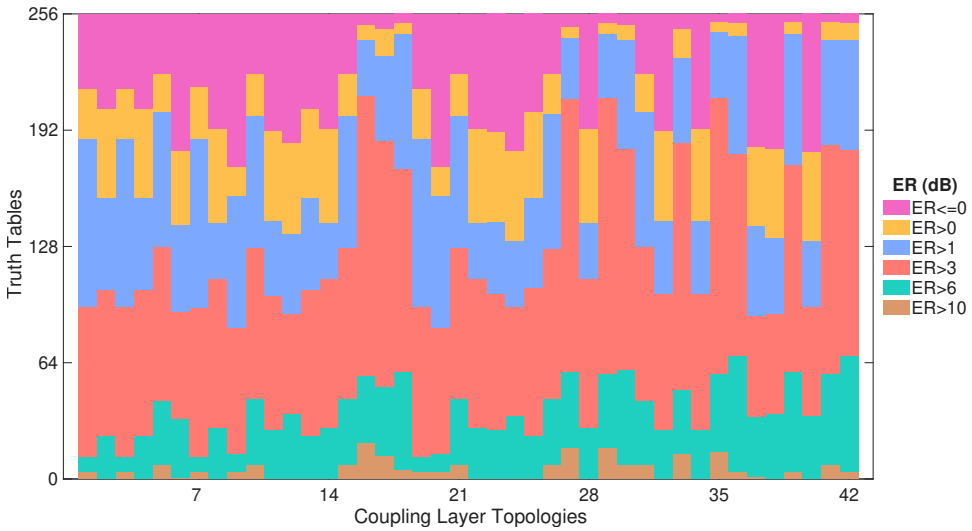


Fig. 3. Histogram of the programmability analysis. For each one of the 42 viable CL topologies, we compute the ER (Eq. (4)) for each of the 256 possible truth tables at the output ports.

TABLE I
EXAMPLE OF A SPECIFIC PHOTONIC LOGICAL OPERATION

X		Expected Output		Obtained Output	
A	***B***	***P (AND)***	***Q (OR)***	***P (AND)***	***Q (OR)***
0	0	0	0	0.2802	0.0692
0	1	0	1	0.0519	0.9766
1	0	0	1	0.0773	0.9779
1	1	1	1	1.0611	1.0046

presence of non-ideal operational conditions, such as power supply noise and measurement uncertainty.

We extended the evaluation of the programmability of the proposed structure to other viable CL topologies. Fig. 3 is a histogram, in which each color represents the ER range obtained from all 42 viable CL topologies on all 256 possible Boolean function combinations at output ports P and Q. From this histogram, we observe that multiple CL topologies can achieve more than 80% of the truth tables with an ER value greater than 3 dB. In addition to the 16th CL topology discussed previously, for instance, in the 35th CL topology where port P connects to ports O_1 and O_2, while port Q connects to ports O_1 and O_3, over 82% of the truth tables have an ER value greater than 3 dB.

IV. CONCLUSIONS AND FUTURE WORK

In this work, we proposed a planar circuital structure to perform programmable photonic logical operations by cascading a viable CL topology after a 3×3 MZI-based Clements mesh. By adopting a hybrid optimization approach that combines the Monte Carlo method and GA, we obtained the phase shift values for each MZI to implement every possible logical operation in each viable CL topology with minimal MSE. Starting from a case study based on a specific selected CL topology, we investigated the programmability of the proposed structure under different viable CL topologies, discovering multiple CL topologies with satisfactory ER performance.

Further investigations can be conducted to fully assess the potential and limitations of the proposed structure by addressing practical issues such as optical coupling, thermal crosstalk, and fabrication variations, integrating these effects into the basic MZI model. In addition, the arrangement of phase shifters can also be further optimized in order to study the scalability of the proposed structure.

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