An Improved Gate Library for Logic Synthesis of Optical Circuits

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***Abstract*—Optical circuits received increasing interest as an alternative to conventional (i.e. electronic) systems – in particular for ultra-high-speed networks and optical interconnects. Consequently, how to design and synthesize the corresponding circuits became an important EDA problem. But existing solutions relied on a restricted gate library leading to rather expensive circuits. In this work, we introduce an improved gate library by providing optical realizations for many further standard operations such as AND, OR, XOR, etc. By this, synthesis approaches can exploit a broader variety of building blocks and, hence, realize circuits of less costs.**

***Index Terms*—Mach-Zehnder interferometer, all-optical synthesis, gate library**

I. Introduction

Optical circuits constitute a new – so-called emerging – technology with which computations are performed on optical rather than electrical signals. This is of interest particularly for ultra-high-speed networks and optical interconnects [11]. In such systems, the respective signals frequently (i.e. at every interconnect interface) need to be transformed from the electrical domain to the optical domain and vice versa. This causes significant overhead which could be avoided if the respective transformations would directly be conducted at the optical signals.

Motivated by this, researchers and engineers evaluated how such optical computations can be realized. This established the field of silicon-based integrated optics (also known as *silicon photonics*) and, hence, the consideration of optical circuits. Realizations of such circuits based on *Mach-Zehnder Interferometer* (MZI) together with *Semiconductor Optical Amplifiers* (SOAs) have been proven to be a suitable and feasible implementation of an optical circuit [4].

These investigations eventually led to the emergence of logic models and, hence, gate libraries to be used for *Electronic Design Automation* (EDA). The so-called (all-optical) MZI gate provides one of the most established atomic element in such libraries. In fact, significant works on the logic design of optical circuits for important Boolean functions such as multiplexers, adders, universal logic blocks, etc. have been conducted by solely relying on this gate library only (see e.g. [2], [9], [4], [5], [10], [12], [13], [18], [26]). Besides that, also automatic synthesis approaches which are capable of realizing arbitrary functionality rely on this library (see e.g. [6], [22], [24], [7]).

However, despite these accomplishments, a gate library solely relying on all-optical MZI gates is restricted to two basic operations only (namely to the two AND operations $x_1.x_2$ and $x_1.\overline{x}_2$ for two given inputs x_1 and x_2). Although this represents a universal building block (i.e. all other functions can be realized from it), it usually leads to rather expensive circuits. In comparison, synthesis of conventional circuits usually also allows for the application of operations such as OR, XOR, XNOR, etc.

In this work, we are aiming to address this problem by providing an improved and extended gate library for the logic synthesis of optical circuits. We thereby consider the corresponding developments from a logic design perspective, but additionally try to respect optical and physical constraints as much as possible. More precisely, we review the optical and physical basics of existing realizations of MZI gates. Based on that, we then propose alternative realizations which employ similar optical and physical effects, but realize alternative functions such as the aforementioned OR, XOR, XNOR, etc. By this, new building blocks are generated which may be used in order to form an improved gate library comprised of a larger set of basic functionality.

In order to evaluate the benefits of the resulting gate library, we discuss how (future) synthesis approaches may exploit the wider variety. In particular, we exemplarily consider an established synthesis scheme based on an *Exclusive-Sum-of-Product* (ESOP) representation of the function to be synthesized. Initial experimental evaluations show how a synthesis scheme based on ESOPs may significantly profit from the improved library. In a similar fashion, the proposed contribution can be exploited for other synthesis approaches as well.

The remainder of this work is structured as follows. The next section reviews the basics of optical circuits as they are established today. Afterwards, the optical and physical foundations leading to the gate library based on MZI gates are reviewed in Section III. This builds the basis for the newly proposed realizations which, eventually, form the improved gate library and are described in Section IV. Finally, the impact of the resulting library on synthesis approaches for optical circuits are discussed and evaluated in Section V, before the paper is concluded in Section VI.

II. Background

An interferometer is an optical device that utilizes the property of interference. Initially, the input beam of light splits into two different beams. The splitting can be done using beam splitters which can be a partially transmissive mirror. The light beams again can be recombined using another beam splitter.

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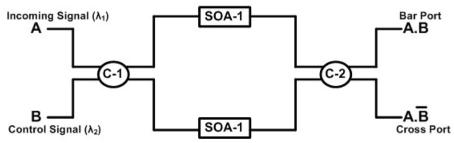
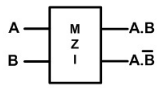


(a) Semiconductor optical amplifier based MZI



(b) Functional schematic of MZI switch

Fig. 1. Schematic diagram of Mach-Zehnder Interferometer

There exists various kinds of interferometers like Mach-Zehnder Interferometer, Michelson Interferometer, Fabry-Perot Interferometer, Sagnac Interferometer, etc. [1]. In this work, we particularly concentrate on the *Mach-Zehnder Interferometer* (MZI) based on *Semiconductor Optical Amplifiers* (SOAs). An SOA-based MZI is an advanced optical device that has the capability of identifying the relative phase difference between light rays which, in turn, helps to analyze different operations on phase and amplitude. SOA-based MZIs have got some distinct advantages in high capacity optical networks where these switches can be used in amplifying the signals. Other advantages are their ease with respect to fabrication, improved quality, thermal stability, small size, and fast switching time.

Fig. 1a shows the schematic diagram of an individual MZI switch, which has two input ports and two output ports. The signal from port A is termed as *incoming signal* with wavelength λ_1 and the signal at port B is known as *control signal* with wavelength λ_2. The two output ports are called *bar port* and *cross port*. At the output ports a band pass filter is present that filters out the control signal B and either passes or blocks the incoming signal A.

Hence, the working principle of an MZI from a functional perspective is as follows:

- If both, the incoming signal at port A and the control signal at port B, are present, then there is a presence of light at the *bar port* and there is no presence of light at the *cross port*.
- If the incoming signal is present at port A and the control signal is absent at port B, then there is presence of light at the *cross port* and no presence of light at the *bar port*.

Presence and absence of light can be represented as logic 0 and logic 1, respectively. We can thus represent the functional behavior of an MZI switch in terms of Boolean algebra as (see Fig. 1b):

$$\begin{aligned} \text{Bar Port} &= A.B \\ \text{Cross Port} &= A.\overline{B} \end{aligned}$$

Using this functional structure of an MZI switch, researchers started to investigate various function realizations using MZI switches as basic building blocks. In fact, various building blocks for important Boolean functions such as multiplexers, adders, universal logic blocks, etc. have been conducted by relying on MZI switches (see e.g. [2], [4], [5], [10], [12], [13], [18], [26]). Besides that, also automatic synthesis approaches which are capable of realizing arbitrary functionality rely on this (see e.g. [6], [22], [24], [7]).

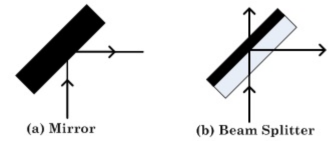


Fig. 2. Reflection and transmission in a mirror and a splitter

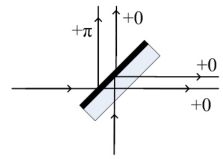


Fig. 3. Function of a beam splitter

III. Working Principle of the MZI Switches

The basic working principle of the MZI switch is based on the constructive and destructive interferences of a pair of light beams that travel along two different paths. When a beam of light is incident on a mirror with a reflective coating on the rear side at an angle of incidence of 45^o, the entire beam gets reflected by 90^o and incurs a phase shift of π. Similarly, when we use a *beam splitter* instead of the mirror, the incoming beam is split into two outgoing beams: (1) the transmitted beam that goes through straight without any deflection and does not incur any phase shift and (2) the reflected beam that gets reflected by 90^o as before with a phase shift of π. The two outgoing beams emerge at an angle of 90^o. The beam splitter can be designed so that the two beams have equal intensity. This is illustrated in Fig. 2.

A beam splitter is typically constructed out of two triangular glass prisms that are glued together through polyester epoxy based adhesives. The thickness of this glue layer is adjusted such that half of the beam incident is reflected and the other half is transmitted, thereby ensuring that there is a 50% chance of reflection and a 50% chance of transmission.

A beam splitter is often provided with metal or dielectric coating for more efficiency. When light is incident on the coated side, there is equal probability of reflection and transmission. In this scenario, a reflection induces a phase shift of π, while transmission induces no phase shift. However, something different happens when light is incident from the back side of the beam splitter: Light first strikes the glass surface and then gets split at glass/metal or glass/dielectric interface. Here again, there is an equal probability of reflection and transmission. However, in this scenario reflection induces no phase shift. This is illustrated in Fig. 3.

The two incoming beams will overlap at the second beam splitter and will emerge as a single light beam. If the two light beams have a phase difference that is an integral multiple of π, *constructive interference* occurs and the corresponding output gives light. On the other hand, if the phase difference is an integral multiple of $\pi/2$, *destructive interference* occurs and the corresponding output produces no light.

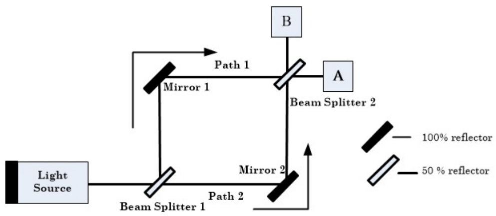


Fig. 4. Mach-Zehnder Interferometer

A *Mach Zehnder Interferometer* (MZI) can be constructed using two mirrors and two beam splitters as shown in Fig. 4 [25]. Here, a light source impinges a beam of light which gets split by *Beam Splitter 1* into two outgoing beams of light with an angle of 90^o between them. These two beams travel along two different paths (*Path 1* as well as *Path 2*) and get reflected on the way by *Mirror 1* as well as *Mirror 2*, respectively. Afterwards, they are re-combined back at *Beam Splitter 2*. The two beams are again split along two paths at an angle of 90^o and received at the two detectors A and B.

Now, we illustrate the phase shifts incurred by the light beams with reference to Fig. 4. Along the path, a light beam traverses, if there is deflection in the path. Then, a phase shift of π occurs which we call *reflection*. If there is no deflection and no phase shift, we call it *transmission*. The total phase shifts incurred by the two beams of lights upon reaching the detectors A and B are defined as follows for the four possible cases (the respective figure denotes the phase shifts):

a) Light source to detector A via Path 1:
   Reflection at Beam Splitter 1 : π
   Reflection at Mirror 1 : π
   Transmission at Beam Splitter 2 : 0
   Total phase shift : 2π
b) Light source to detector A via Path 2:
   Transmission at Beam Splitter 1 : 0
   Reflection at Mirror 2 : π
   Reflection at Beam Splitter 2 : π
   Total phase shift : 2π
c) Light source to detector B via Path 1:
   Reflection at Beam Splitter 1 : π
   Reflection at Mirror 1 : π
   Reflection at Beam Splitter 2 : π
   Total phase shift : 3π
d) Light source to detector B via Path 2:
   Transmission at Beam Splitter 1 : 0
   Reflection at Mirror 2 : π
   Transmission at Beam Splitter 2 : 0
   Total phase shift : π

Therefore, the pairs of beams that reach detectors A and B will incur phase differences of $(2\pi - 2\pi) = 0$ and $(3\pi - \pi) = 2\pi$, respectively. Hence, there will be a *constructive interference* in both detectors. However, for logic design applications, we need to switch a light beam on and off based on the input beams and, hence, we require constructive interference in one detector and destructive interference in the other.

Using the principle illustrated in Fig. 3, we can design an MZI that ensures constructive and destructive interferences in the two detectors. This is illustrated in Fig. 5, where the dielectric coating in the two beam splitters are shown. With reference to this configuration, we shall again examine the overall process by considering beam splitter, optical path length t (product of thickness of beam and its refractive index), and distance traveled by light through Path 1 and Path 2 (say, $L1$ and $L2$). We refer to Beam Splitter 1, Beam Splitter 2, Mirror 1, and Mirror 2 by BS1, BS2, M1, and M2, respectively.

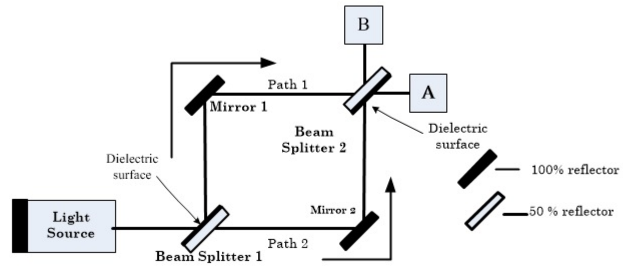


Fig. 5. MZI using dielectric coating in beam splitters

For detector A, Path 1 picks up the following phase shifts: π due to reflection at BS1, π due to reflection in M1, nothing at the transmission in BS2, $\frac{2\pi L_1}{\lambda}$ for the distance traveled, and $\frac{2\pi t}{\lambda}$ for the optical path length covered in glass substrate of BS2. This gives a total phase shift of

$$2\pi + 2\pi \left(\frac{L_1 + t}{\lambda} \right).$$

Path 2, also on its way to detector A, picks up the following phase shifts: nothing at BS1, π at M2, and π again at BS2, $\frac{2\pi L_2}{\lambda}$ for the distance traveled, and $\frac{2\pi t}{\lambda}$ from passing through the glass substrate at BS1. This gives a total phase shift of

$$2\pi + 2\pi \left(\frac{L_2 + t}{\lambda} \right).$$

Hence, the phase difference between the two paths reaching detector A is

$$\begin{aligned} \theta_1 &= 2\pi + 2\pi \left(\frac{L_1 + t}{\lambda} \right) - 2\pi - 2\pi \left(\frac{L_2 + t}{\lambda} \right) \\ &= 2\pi \left(\frac{L_1 - L_2}{\lambda} \right) = \delta, \end{aligned}$$

where δ is the phase shift due to the difference in the path lengths.

In a similar way, we can calculate the phase difference between the two paths on their way to detector B. Here, Path 1 picks up the following phase shifts: π at BS1, π at M1, nothing at the reflection in BS2 (as it is hitting the rear side), $\frac{2\pi L_1}{\lambda}$ for the distance traveled, and $\frac{2\pi t}{\lambda}$ for the optical path length covered in glass substrate of BS2. This gives a total phase shift of

$$2\pi + 2\pi \left(\frac{L_1 + t}{\lambda} \right).$$

Path 2, also on its way to detector B, picks up phase shifts of: nothing at BS1 and BS2, π at M2, $\frac{2\pi L_2}{\lambda}$ for the distance travelled, and $\frac{2\pi t}{\lambda}$ because of optical path length of glass material. This gives a total phase shift of

$$\pi + 2\pi \left(\frac{L_2 + t}{\lambda} \right).$$

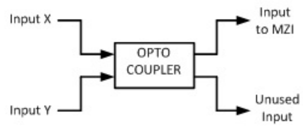
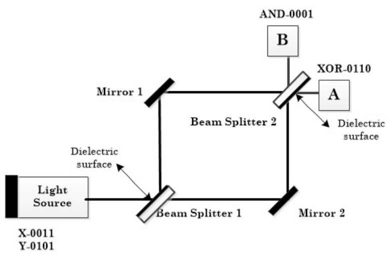


Fig. 6. Combining two inputs using opto-coupler



(a) MZI setup

X	Y	Detector A (XOR)	Detector B (AND)
0	0	0 (No light)	0 (No light)
0	1	1 (constructive interference)	0 (π phase difference)
1	0	1 (constructive interference)	0 (π phase difference)
1	1	0 (destructive interference)	1 (constructive interference)

(b) Resulting inputs/outputs

Fig. 7. Implementing the XOR and AND function

Hence, the phase difference between the two paths at detector B is

$$\begin{aligned}\theta_2 &= 2\pi + 2\pi\left(\frac{L_1 + 2t}{\lambda}\right) - \pi - 2\pi\left(\frac{L_2 + 2t}{\lambda}\right) \\ &= \pi + 2\pi\left(\frac{l_1 - l_2}{\lambda}\right) = \pi + \delta.\end{aligned}$$

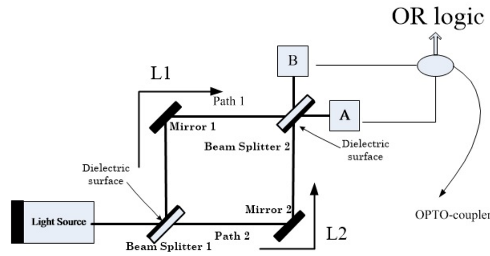
Now we can infer that, if $\delta = 0$, there will be *constructive interference* on the path to A and *destructive interference* on the path to B. Similarly, if $\delta = \pi$, the reverse will happen.

IV. Proposed Gate Library

Based on the discussions from the previous sections, it is now possible to realize different types of logic functions by exploiting the phase difference between the two arms (Path 1 and Path 2) of an MZI. In all the gate implementations discussed in the following subsections, we assume that there are two optical inputs X and Y that are combined through an opto-coupler [8] and then fed to *Light Source* input of the MZI. The process of combining two optical inputs into a single light source is depicted in Fig. 6.

A. Configuration 1: AND and XOR Function (Half Adder)

Here, let assume that the path lengths L1 and L2 are equal, so that the phase difference at detector A will become 0 and at detector B will become π (see Fig. 7a). Now, if we apply the inputs at X and Y, then the truth table for the two detector outputs will be as shown in Fig. 7b. We can say that we have implemented a half adder using a single MZI, where the *sum* and *carry* outputs are obtained at the detectors A and B, respectively.

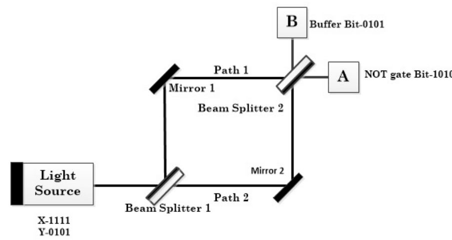


(a) MZI setup

X	Y	Detector A	Detector B	A + B (OR)
0	0	0	0	0
0	1	1	0	1
1	0	1	0	1
1	1	0	1	1

(b) Resulting inputs/outputs

Fig. 8. Implementing the OR function



(a) MZI setup

X	Y	Detector A (NOT gate)	Detector B (Buffer)
1	0	1 (Constructive inter.)	0 (π phase difference)
1	1	0 (π phase difference)	1 (Constructive inter.)

(b) Resulting inputs/outputs

Fig. 9. Implementing the inverter and buffer

B. Configuration 2: OR Function

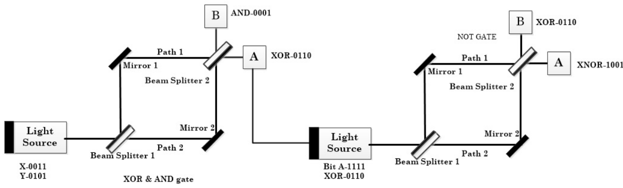
If we combine the outputs from the detectors A and B in Fig. 7a using an opto-coupler, we can implement the OR function (see Fig. 8a and Fig. 8b).

C. Configuration 3: Inverter and Buffer

For implementing inverter and buffer, we will provide one input (X) as constant 1 and apply the input Y at the other. As shown in Fig. 9a and Fig. 9b, the inverter function is implemented at detector A, while the buffer function is implemented at detector B.

D. Configuration 4: XNOR Function

The XNOR function can be implemented by cascading two MZIs as shown in Fig. 10a. In this setup $A1$ realizes the XOR function which is fed as the input to the next MZI. The final output is $A2$ which realizes the XNOR. Since $B2$ is just the complement of $A2$, $B2$ will realize the XOR function (see Fig. 10b).

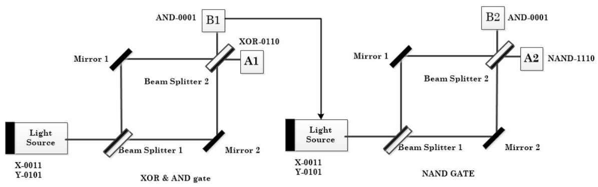


(a) MZI setup

X	Y	A1 (XOR)	B1 (AND)	A2 (XNOR)	B2 (XOR)
0	0	0	0	1	0
0	1	1	0	0	1
1	0	1	0	0	1
1	1	0	1	1	0

(b) Resulting inputs/outputs

Fig. 10. Implementing the XNOR function



(a) MZI setup

X	Y	A1 (XOR)	B1 (AND)	A2 (NAND)	B2 (AND)
0	0	0	0	1	0
0	1	1	0	1	0
1	0	1	0	1	0
1	1	0	1	0	1

(b) Resulting inputs/outputs

Fig. 11. Implementing the NAND function

E. Configuration 5: NAND Function

The NAND function can be implemented by using a cascade of two MZIs as shown in Fig. 11a. A NAND gate with one MZI is not possible as we cannot generate a 1 from a 00 combination because physically we cannot generate a light without a light in first place. In this setup, $B1$ implements the AND function which is fed as the input to the next MZI. The final output is $A2$ which realizes the NAND. Since $B2$ is the complement of $A2$, it realizes AND (see Fig. 11b).

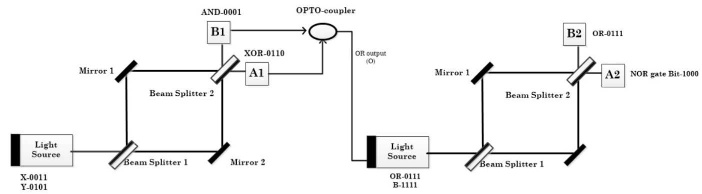
F. Configuration 6: NOR Function

The NOR function can also be implemented using a cascade of two MZIs and one opto-coupler, i.e. OR and NOT. Again, a NOR implementation with just one MZI is not possible as we cannot generate a 1 from a 00 combination. In this setup, the output of the opto-coupler (O) gives the OR function which is fed as input to the next MZI. The final output is $A2$ which realizes the NOR function. Since $B2$ is the complement of $A2$, it will realize the OR function (see Fig. 12a and Fig. 12b).

V. Discussion and Application

Having the all-optical realizations presented in the previous section, an improved gate library results which is not solely composed of an AND gate (with cost of 1 MZI switch) but includes gates for

- AND, XOR, OR, and NOT (with costs of 1 MZI switch), as well as
- XNOR, NAND, and NOR (with costs of 2 MZI switches).



(a) MZI setup

X	Y	O (OR)	A2 (NOR)	B2 (OR)
0	0	0	1	0
0	1	1	0	1
1	0	1	0	1
1	1	1	0	1

(b) Resulting inputs/outputs

Fig. 12. Implementing the NOR function

In contrast, previously proposed approaches [4], [6], [12], [15], [26] had to generate these functions from the building block reviewed in Section II. Consequently,

- NOT, AND, OR, as well as NOR functions required 1 MZI switch,
- NAND as well as XOR functions required 2 MZI switches, and
- the XNOR function required 3 MZI switches.

Hence, the proposed library will likely lead to less costly circuits which additionally are easier to synthesize.

In order to further demonstrate that, we exemplary consider a synthesis approach based on *Exclusive-or Sum-Of-Products* (ESOP). Here, a function is expressed as an XOR of several product terms, where the literals in the product terms may appear in complemented or uncomplemented forms. Because of that, an ESOP expression can directly be mapped to a netlist composed of NOT, AND, and XOR gates. Using the proposed library, each of these functions can be realized by a single MZI switch only. In contrast, the previously applied library could realize the NOT and the AND by a single MZI switch, but required two MZI switches in order to realize the XOR.

Example 1. *Consider the ESOP expression* $f = x_1.x_2.x_4 \oplus x_2.x_4.x_5 \oplus x_1.x_3 \oplus x_6$. *To realize this function, we require two 2-input AND gates to realize the product term* $x_1.x_2.x_4$*, another two AND gates for* $x_2.x_4.x_5$*, and one AND gate for* $x_1.x_3$*. In order to XOR the four product terms, we need three 2-input XOR gates. In other words, we need a total of 8 MZI switches in order to realize this circuit using the improved gate library. In contrast, the previously applied library would require a total of 11 MZI switches.*

In general, consider a given single-output function for which there are m product terms $P_1, P_2, \ldots, P_m$ with t of the variables appearing in complemented forms. Also, let L_i denote the number of literals (in complemented or uncomplemented form) in the product term P_i. Then, the total number of operations can be estimated as follows:

$$\begin{aligned} \text{No. of 2-input AND gates} &: \sum_{i=1}^{m}(L_i - 1) \\ \text{No. of 2-input XOR gates} &: m - 1 \\ \text{No. of NOT gates} &: t \end{aligned}$$

TABLE I
EXPERIMENTAL EVALUATION

Benchmark	#inputs	#outputs	#cubes	#MZI with library		
				Previous	Proposed	% Imp.
3_17_6	3	3	5	21	14	33.3
9symml_91	9	1	52	439	386	12.1
apex2_101	39	3	1663	36363	34581	4.9
apex4_102	9	19	634	13336	8223	38.3
cordic_138	23	2	776	12955	11411	11.9
ex5p_154	8	63	72	1395	854	38.8
f51m_159	14	8	312	3080	2719	11.7
mixex3_180	14	14	518	6856	5681	17.1
spla_202	16	46	269	4475	3689	17.6
urf3_75	10	10	842	9659	7370	23.7

Using the proposed library, this results in a total of

$$\sum_{i=1}^{m}(L_i - 1) + (m - 1) + t \text{ MZI switches}$$

while previously proposed approaches required a total of

$$\sum_{i=1}^{m}(L_i - 1) + 2(m - 1) + t \text{ MZI switches.}$$

In order to experimentally evaluate the differences, we prototypically implemented the sketched ESOP-based synthesis scheme and applied benchmark functions to it which have been generated using *Exorcism-4* [19]. Table I lists the resulting numbers with respect to the previously applied gate library and the proposed library (additionally the number of primary inputs, primary outputs, and products are given).

The results clearly show the improvement possible by the proposed gate library. In fact, just changing the gate library (without any adjustments of the synthesis approach) reduces the number of MZI switches in all cases. In the best cases, reductions of up to one Third are possible.

VI. Conclusion

In this work, we proposed an improved gate library for the synthesis of optical circuits. To this end, we studied the working principle of Mach-Zehnder Interferometer and, based on that, derived new configurations eventually realizing further building block functions, namely AND, XOR, OR, negation, XNOR, NAND, as well as NOR. From those realizations, a new gate library has been formed which allow for the synthesis of optical circuits at significantly less costs. All considerations have been conducted from a logic design perspective, although optical and physical constraints have been respected as much as possible. The resulting gate library may provide the basis for several further synthesis approaches to be developed in the future.

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