

Tutorial: Slow and Non-volatile Phase shifters for Large-Scale Programmable Photonics

Wim Bogaerts

Photonics Research Group - Ghent University - imec, Ghent, Belgium

Email: wim.bogaerts@ugent.be

Abstract—As photonic circuits become larger, they require more actuators for tuning, trimming or configuration. The requirements on these actuators differ from high-speed modulators - compactness, low power, and even nonvolatility. In this tutorial we give an overview of the different technologies.

Index Terms—electro-optic actuators, nonvolatile actuators

I. INTRODUCTION

Photonic Integrated Circuits are rapidly scaling to more complex functionality, combining multiple optical IO channels, high-speed modulation inputs and photodetector outputs, as well as signal mixing and wavelength filtering functions [1]. As most photonic circuits are analog in nature, the scale to larger circuits also accumulates fabrication imperfections, and these require tuning and/or trimming mechanisms to correct. Also, some functionality needs to be actively tuned (e.g. wavelength filtering). We have also, in the past decade, seen the emergence of programmable photonic circuits [2], where the paths of light can be actively reconfigured. All these circuits require an increasing number of tuning elements, usually in the form of an electro-optic phase shifter, actuated by an electrical drive circuit.

II. REQUIREMENTS

What makes a good actuator for large scale photonic integrated circuits? We can identify multiple metrics that can guide our selection [3]–[5]. In most cases, our actuator will be used to redirect light or induce a phase shift, so it should have a low optical loss. That's why, in photonic circuits, we prefer a phase shifter to an attenuator. After all, a phase shifter can be converted into an attenuator by embedding it in a Mach-Zehnder interferometer (MZI). As light often has to pass through multiple devices, the insertion loss is often the most critical evaluation criterion. Next is the strength of the underlying physical effect. Which can roughly be translated into the length of the device needed to induce a π phase delay. This also relates to the actual optical length for the devices, which is relevant for circuits where short paths are needed (e.g. inside a ring small ring resonator). It also relates to the footprint of the device, which has a major impact on the

cost of the chip as the number of actuators scales. Note that footprint does not just encompass the physical dimensions of the actuator device, but often also its optical and electrical access ports, and even the area it influences (e.g. through thermal crosstalk). Other metrics to be considered are the power consumption, which can be broken down in dynamic (during a change) and static (when there is no change). In non-volatile devices, the static power consumption is effectively zero. Most actuators are electrically controlled, which also puts constraints on the driving scheme (DC, pulsed), the operating voltages, and the easy with which it can be integrated into a control loop (e.g. linearity, hysteresis effects). And in the end, the actuators need to be integrated, by the thousands, on a chip together with all the other PIC functionalities, so processing compatibility and fabrication yield become a prime concern.

III. ELECTRO-OPTIC PHASE SHIFTER IMPLEMENTATIONS

There are many implementations of electro-optic phase shifters, depending on the underlying PIC technology platform. We briefly list the key mechanisms used

- **Thermo-optic tuning:** This is usually implemented in the form of a resistive heater integrated inside or near the waveguide. The temperature change effects a change in the refractive indices, and thus a phase delay. This requires constant burn of electrical power to maintain, and the heat dissipation can also cause crosstalk to neighbors. Still, this is the most used phase shifter because of its simplicity, maturity and high yield.
- **Carriers (plasma dispersion):** Manipulating carrier density in semiconductors can tune the phase, but it also induces a change in absorption. Generally, this is used for high-speed modulators, less for low-speed circuit tuners.
- **Pockels effect:** This linear electro-optic effect is fast, but quite weak (i.e. long devices), and requires materials with a high $\chi^{(2)}$ (e.g. lithium niobate, BTO, polymers). They are today mostly explored for high-speed modulators.
- **Liquid Crystals** are used today mainly for (micro-)displays, but they can also be integrated on photonic chips to implement quite effective phase shifters. Of course, this requires good management of the liquid on the chip, and electronics that support the typical AC driving schemes that liquid crystals require [6].
- **Micro-electromechanical systems (MEMS):** These consist of movable elements on the chip, which can be actuated electrostatically or through piezo elements. The

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physical movement induces a very strong effect, but because the devices are suspended they can also be somewhat fragile. The electrical power consumption can be very low if there are no leakage current paths [7].

- Stress: Piezo materials can also be used to induce stress in the waveguides. This is a relatively weak effect, requiring long actuators, but with very low added insertion loss [8].

All of these actuators come with their own strengths and weaknesses, and they all require a constant electrical control (even if they have very low static power consumption).

Volatile	Speed	Power/ π (static)	Length/ π	Key challenge	TRL
Heaters	μ s	1-20mW	10 μ m	Power, crosstalk	9
Carriers	10ps	μ W-mW	200-2000 μ m	Insertion loss	9
Pockels	1ps	nW- μ W	1-10mm	Length	6
Piezo	ns	nW	1-10mm	Length, footprint	8
Liquid Crystal	100 μ s	μ W	100 μ m	Integration	3
MEMS	μ s	nW	50 μ m	Integration, reliability	4
Non-volatile	Speed	Power/ π (dynamic)	Length/ π	Key challenge	TRL
Heaters	ms-s	>100mW	100 μ m	Control	5
Ferro-electric	μ s-ms	μ W-mW	100 μ m	Lifetime	3
PCM	μ s-ms	100mW	20 μ m	Multilevel, lifetime	4
Polymers	ms-s	100mW	40 μ m	Multilevel, lifetime	2
Latching MEMS	ms-s	nW- μ W	50 μ m	Multiple drive channels	3
Polymerizable LC	s	10mW	100 μ m	Single-use	2

Fig. 1. Overview of volatile and nonvolatile phase shifters

IV. NON-VOLATILE PHASE SHIFTERS (PERMANENT AND NON-PERMANENT)

In contrast, non-volatile phase shifters do not need permanent driving: As they are non-volatile, they can maintain their state after it has been set. Some key examples of non-volatile actuation mechanism are

- Phase Change Materials: These are materials with two or more stable states (e.g. crystalline and amorphous) with very different optical properties. By using the correct thermal cycling, the material can be (partially) converted from one state into the next [9].
- Ferro-electric domains in Pockels materials: Many Pockels materials are, after deposition, polycrystalline, and exhibit ferro-electric domains. Applying an electric field can force these domains to flip, changing the refractive index for a propagating wave [10].
- Polymers can also be actuated to exhibit multiple permanent states, either by manipulating their porosity or by mixing multiple compounds. Like with PCM, the indirect actuation mechanism is a thermal cycle [11].
- Liquid crystals are a non-volatile actuation mechanism, but when combined with polymerizable compound, they can permanently change a photonic circuit. This is a one-time action, to it cannot be reversed or altered later [12].

- A similar trimming mechanism is based on stress induced inside or around the waveguide. This can be done using UV light or electron-beam writing [13].
- MEMS devices can also be designed for nonvolatile operation. Using deliberate contact surfaces to provide stiction, combined with a push-pull actuator to release the device, it is possible to make nonvolatile switches. And by using separate clamping actuators, even analog tuners can be made non-volatile.
- Even the simple thermal tuners have already been shown to exhibit nonvolatile operation. By excessively raising the temperature around the waveguide, a permanent change is induced (e.g. annealing) resulting in a permanent tuning [14], [15].

V. ADVANTAGES AND CHALLENGES OF NONVOLATILE TUNING

The capability of nonvolatile tuning might seem to be all winning. The key advantages are obvious

- No static power consumption, making it possible to tune the device once and then detach it from its electronic power supply.
- For some techniques, there is even no need for electronics, as the effect can be induced by laser writing or another no-contact method. However, many of the mechanisms discussed above still come with some challenges.
- The tuning scheme often involves a step where the circuit is heavily deregulated (e.g. phase change materials need a high temperature for a short duration, which will affect the actuator but also induce thermal crosstalk). This means that hitless operation is not possible: the circuit will be offline for a short period during reconfiguration.
- Such tuning mechanism also make it difficult to actively control the state with an electronic feedback loop. Especially when the effect has serious hysteresis.
- Nonvolatile states are often difficult to control precisely, especially in intermediate tuning levels. The precision is therefore often limited to 5 or 6 bits.
- Some mechanisms degrade over time (e.g. ferroelectric domains or microcrystals coagulate and form larger domains, changing the tuning curve and reducing precision.)
- Even with nonvolatile tuners, the chip might still be susceptible to global temperature change or drift mechanisms, requiring still some active tuning capability.

VI. CONCLUSION

Overall, the use of nonvolatile photonic actuators adds a capability to the ecosystem that could be extremely useful in large circuits. Trimming circuits to improve overall yield could already be a crucial advantage, but also circuits where reconfiguration is infrequent are good candidates. Still, it is expected that nonvolatile actuators will be used side by side with the traditional electro-optic phase shifters, where a lot of new concepts are still being actively developed.

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