

Optimization of an integrated optical crossbar in SOI technology for optical networks on chip

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Abstract—In this paper a novel design for an optical network on chip (ONoC), enabling optical on-chip signal routing, is presented. Requirements for such a network are defined and the design of ONoC passive components is described and validated by experimental results.

Keywords—integrated optics, optical interconnections, optical filtration, add-drop filters, microdisk resonators, SOI waveguides.

1. Introduction

Electrical intra-chip or inter-chip interconnects will constitute a major bottleneck to the improvement of performance of very deep sub-micron technologies (half-pitch under $0.1 \mu\text{m}$). Predicted limitations are formulated in terms of power consumption and latency for intra-chip interconnects and bandwidth for inter-chip interconnections. Optical solutions should enable the industry to address these problems. For example, an optical network on chip (ONoC) enables high bandwidth and low contention routing of data using wavelength multiplexing.

2. Principles of optical network on chip

The 4×4 ONoC is presented in this section. The basic element is an optical crossbar based on passive add-drop filters, described hereafter.

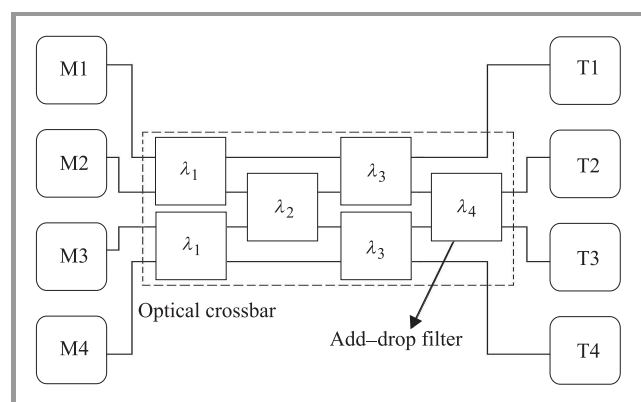


Fig. 1. A schematic overview of the 4×4 ONoC.

Figure 1 illustrates the 4×4 ONoC. The symbols M (masters) and T (targets) represent electronic subsystems (including the optoelectronic interface which is outside

the scope of this paper) that need to communicate with each other. The core of the optical system, called a crossbar, is a fully passive network, based on wavelength routing. Each cell λ_i of this crossbar is a wavelength selective add-drop filter. The crossbar has to be completely reversible (each master can become a target and each target can become a master).

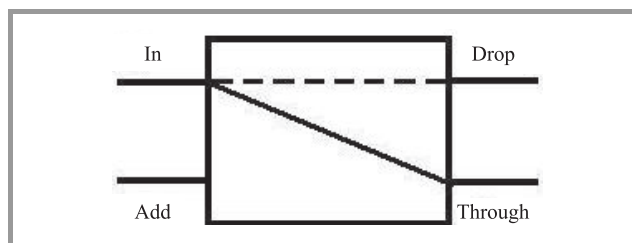


Fig. 2. Signal routing of the elementary add-drop filter (for 4×4 ONoC).

Figure 2 presents the design requirements for the add-drop filter in the 4×4 ONoC. In order to totally connect all the master ports with all the targets a specific design of

	T1	T2	T3	T4
M1	λ_2	λ_3	λ_1	Non resonance
M2	λ_3	λ_4	Non resonance	λ_1
M3	λ_1	Non resonance	λ_4	λ_3
M4	Non resonance	λ_1	λ_3	λ_2

Fig. 3. Operation truth table of 4×4 ONoC.

the filter is necessary. For four ports placed on two parallel waveguides, it transmits non resonant wavelengths in the diagonal direction, and it drops resonant wavelengths in the straight direction. This phenomenological description allows us to establish the operation table of the crossbar given in Fig. 3.

3. Optical crossbar design

The key building blocks of the optical crossbar are the wavelength selective add-drop filters. In this section we take into consideration two types of add-drop filters: a single-disk device and a filter based on two coupled disks. Figure 4 shows a rather complex waveguide routing scheme necessary to achieve the properties described in Fig. 2, when implementing a single-disk add-drop filter (referred to hereafter as filter A) into the optical crossbar. One can notice two intersections potentially incurring additional crosstalk and attenuation.

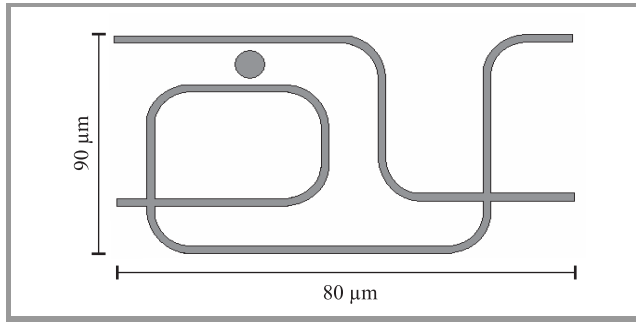


Fig. 4. Single microdisk add-drop filter waveguide routing scheme.

An alternative structure uses filters with forward dropping direction, which is the case of filters with two identical coupled microdisks, presented in Fig. 5 (referred to hereafter as filter B) [3]. This allows a simpler routing design with

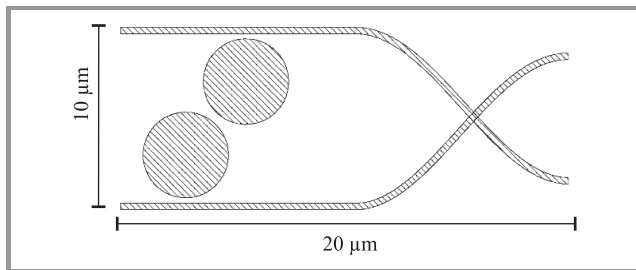


Fig. 5. Coupled two-microdisk add-drop filter waveguide routing scheme.

a smaller number of crossings. But such filters may be more sensitive to fabrication defects, such as slightly different disk radii or a difference of coupling between disks and guides.

4. Fabrication of the optical crossbar demonstrators

Both types of crossbars have been fabricated using SOI technology of CEA-LETI in Grenoble, which allows compact integration and is compatible with silicon microelectronics. Deep UV photolithography has been used to fabricate the samples. In the crossbar based on filter A (Fig. 6),

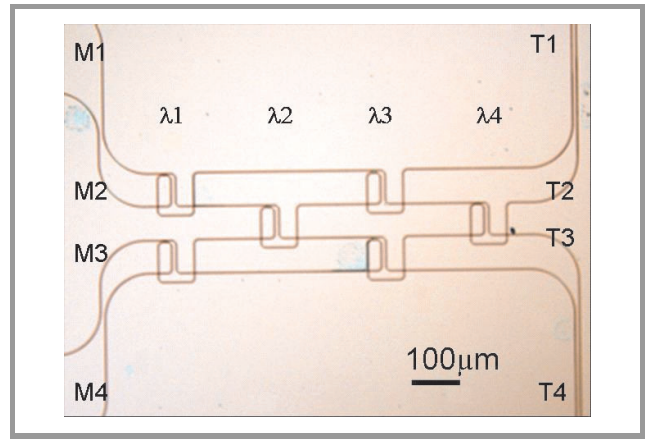


Fig. 6. Demonstrator of ONoC based on single-disk add-drop filters. Radii: 1.5 μm (λ_1), 2 μm (λ_2), 2.5 μm (λ_3), 1 μm (λ_4).

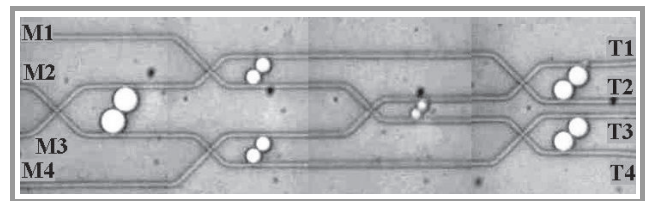


Fig. 7. Demonstrator of ONoC based on coupled two-disk add-drop filters. Radii: 2.5 μm (λ_1), 1.5 μm (λ_2), 1 μm (λ_3), 2 μm (λ_4).

the bend radius has to be large enough to avoid radiative losses; it is then far less compact than the crossbar based on filter B (Fig. 7).

5. Optical crossbar characterization results

The crossbars have been characterized using an edge coupling insertion losses optical bench. The source used in the characterization is a tuneable laser. An InGaAs CCD allows the observation of the top scattered light.

5.1. Characterization of the optical crossbar based on single-disk add-drop filter A

Figure 8 presents the light switching in the optical crossbar, depending on the injected wavelength. Light is injected to the input M1 and subsequently collected at the outputs T1...T4. At the wavelength of 1530 nm a non-resonant transfer to port T4 is observed (Fig. 8a); at 1515.3 nm, the signal is dropped to port T3 (Fig. 8b); at 1510.55 nm, to T2 (Fig. 8c), and at 1508 nm, to port T1 (Fig. 8d). One can notice the directional transfer of most of the signal at the resonant dropping wavelengths of the filters λ_1 , λ_2 , λ_3 . The bright points correspond to scattered losses at waveguide intersections.

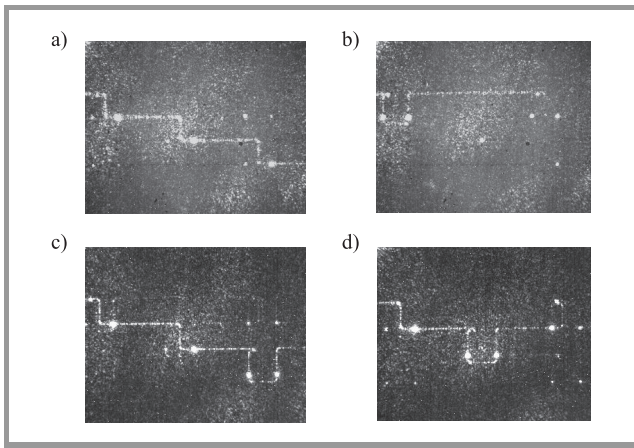


Fig. 8. Images of crossbar based on single-disk filter for wavelengths: (a) 1530 nm; (b) 1515.3 nm; (c) 1510.55 nm; (d) 1508 nm injected into port M1.

Table 1 reports the transfer wavelengths of most of the different routing configurations. It should be noted that filter λ_4 does not exhibit any resonant wavelength: due to the fact that its radius is too small ($1 \mu\text{m}$), the resonant gallery

Table 1

Transfer wavelengths [nm] of the crossbar based on single-disk filter

Port	T1	T2	T3	T4
M1	1508	1510	1515.5	Non resonance
M2	1510	Impossible	Non resonance	1515.5
M3	1515.5	Non resonance	Impossible	1510
M4	Non resonance	1515.5	1510	1508

modes suffer from high losses. This makes it impossible to route the signal from port M2 to T2 and from port M3 to T3.

5.2. Characterization of the crossbar based on coupled two-disk add-drop filter B

Figure 9 presents the experimental spectra of the optical crossbar based on add-drop filter B. In this figure non-resonant transmission from port M1 (see Fig. 7 for reference) to port T4 is presented. One can also observe resonance dropping of the signal to port T3 (with the wavelength of 1513 nm) and to port T2 (1520 nm). The wavelength of 1513 nm is the resonance wavelength of the filter with disk radii of $2 \mu\text{m}$ and the 1520 nm of the one with disk radii of $1.5 \mu\text{m}$. The free spectral range of 50 nm is also shown in this figure. Dropping from port M1 to port T1 is impossible due to incorrect operation of the add-drop filter with disk radius of $1 \mu\text{m}$.

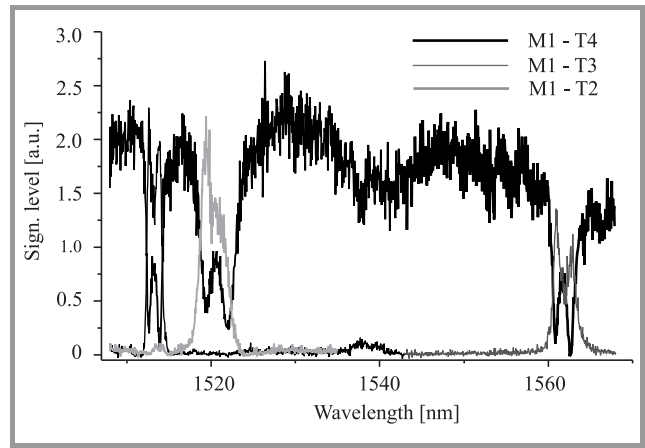


Fig. 9. Transmission spectra of the signal injected into port M1 and collected at the different outputs of the optical crossbar based on coupled two-disk add-drop filter.

A close-up of the optical crossbar transmission spectrum is presented in Fig. 10. One can observe a splitting in the resonance peak caused by the strong coupling between the microdisk resonators of add-drop filters. The low quality

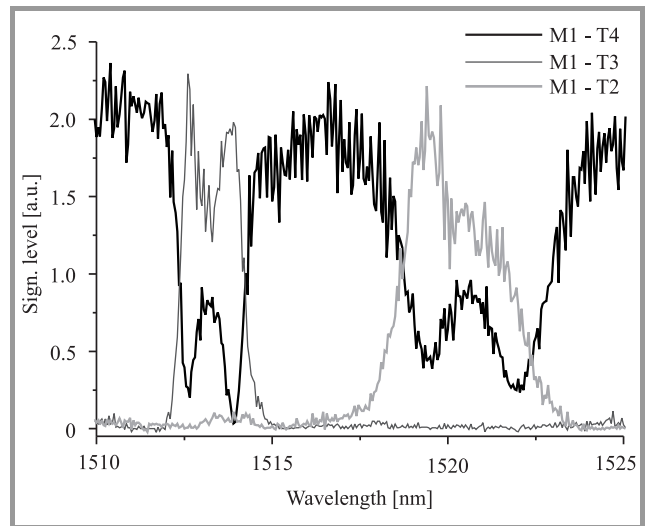


Fig. 10. Close-up of the transmission spectra of the optical crossbar in the range of 1510–1525 nm.

factor of these resonant peaks is caused by strong coupling between the disks and the waveguides. Due to the smaller radii of the resonators ($1.5 \mu\text{m}$ versus $2 \mu\text{m}$) the gallery mode confinement at 1520 nm is much weaker than at 1513 nm. This weaker confinement results in a wider peak and a lower quality factor at 1520 nm than at 1513 nm.

6. Optimization of the optical crossbar: the improved design of the filter

Both designed types of crossbar are operational and allow 4×4 optical communication. Although they suffer from

imperfections and cannot be directly applied without improvements, they show that the ONoC does operate as predicted. As an improvement to the basic structure we now present an improved type of channel-dropping filter based on two microdisk resonators which, when used in an optical crossbar, can potentially both amplify the strong points and reduce the weaknesses of both types of crossbar that were previously presented.

6.1. Operation principles of the cross based two-disk add-drop filter

In Fig. 11 a design for a cross based two-disk add-drop filter (referred to hereafter as filter C) is presented. It consists of two microdisk resonators coupled with the waveguide

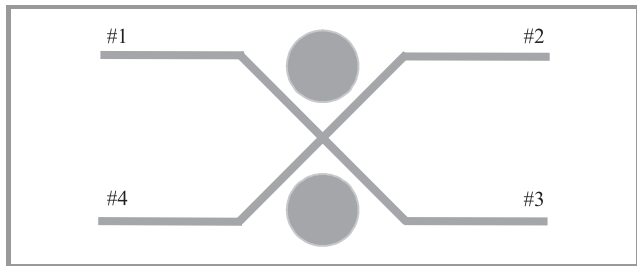


Fig. 11. Design of a novel type of add-drop filter based on two-microdisk resonators.

intersection. This type of design described in [4] has several advantages:

- it allows simpler waveguide routing compared to the 1st type of add-drop filter;
- thanks to the central symmetry the properties of the filter do not depend on the port into which the transmitted signal is injected;
- due to the fact that the two microresonators are coupled via waveguides it is not as sensitive to micro-

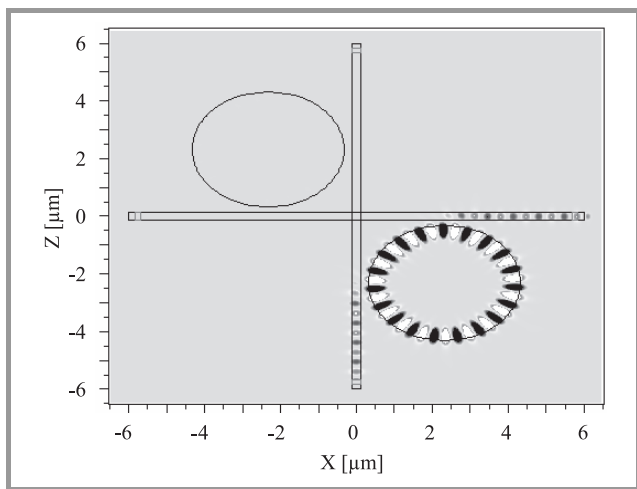


Fig. 12. The 2DFDTD simulation of electromagnetic field distribution for resonant wavelength of 1570 nm.

resonator imperfections as add-drop filter B (more particularly, a difference between the radii of the two-disk filter B drastically reduces the transmittance, whereas it introduces only a split in the transmittance spectrum of the filter C).

Figure 12 displays the 2DFDTD simulation of the add-drop filter C. At the resonant wavelength the light is fully removed from the injection waveguide and dropped to the output waveguide through the gallery mode of the first disk “met” by the light, as shown in Fig. 12. Thus at this wavelength losses of the waveguide intersection do not affect the level of the dropped signal.

6.2. Design of the optical crossbar based on add-drop filters C

The above mentioned advantages of the cross based add-drop filter allow the design of an optical crossbar that should be a good compromise between the properties of the two crossbar designs described earlier in this paper. It should also eliminate their weaknesses.

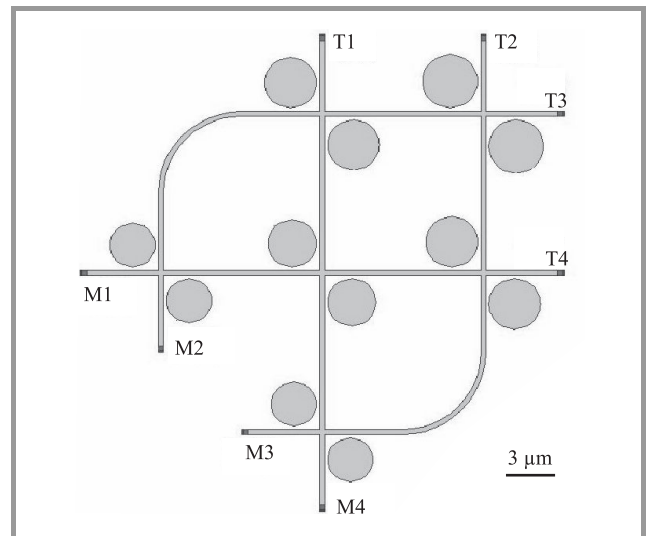


Fig. 13. Design of the optical crossbar with add-drop filters C.

Figure 13 presents the design of the optical crossbar with add-drop filters C. This design is very promising due to the minimized number of intersections and reduced area compared to the crossbar with add-drop filters A. With this design we can also avoid the problems with disk uniformity-very important in the crossbar with add-drop filters B. In this design we implemented microdisk resonators with the radii of 1.5 μm, 1.55 μm, 1.6 μm and 1.65 μm.

6.3. The 2DFDTD simulations of the 3rd type add-drop filter based crossbar

The operation of the optical crossbar has been validated with 2DFDTD simulation. Figure 14 presents the simulation spectra of the transmission from input port M1 to the four output ports. One can observe dropping to all

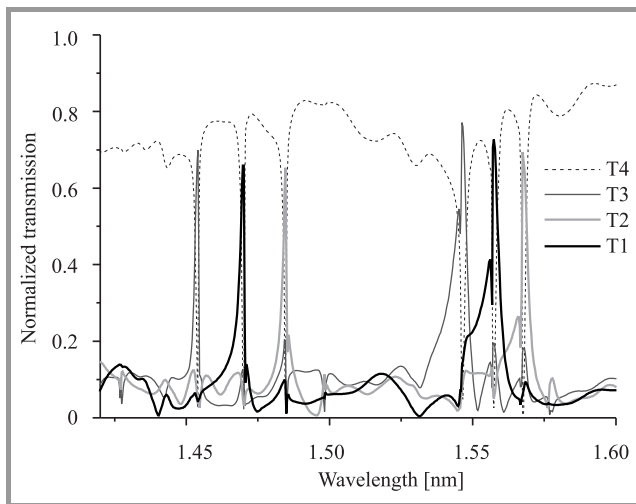


Fig. 14. The 2DFDTD simulation of the optical crossbar with add-drop filters C.

the output ports with a signal level better than 70% between 1500 nm and 1600 nm and the free spectral range of about 100 nm for the filters with radii of 1.5 μm , 1.55 μm and 1.6 μm .

7. Conclusions

Two types of 4×4 optical crossbars have been designed, fabricated and characterized. Both crossbars have been demonstrated to operate correctly despite losses. These losses occur mainly either at waveguide intersections in the case of the crossbar based on single-disk filter, or in the microdisks themselves in the case of the crossbar based on coupled two-disk filter. The introduction of a new type of filter, with two uncoupled disks separated by a single crossing may both enable a simple design and reduce the losses.

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Frederic Gaffiot and **Zbigniew Lisik** – for biographies, see this issue, p. 108.