16x25 GHz Optical OFDM Demultiplexer in a 220nm Silicon Photonics Platform using a Parallel-Serial Filter Approach

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Abstract *A multi-arm Mach-Zehnder interferometer based filter architecture is employed to demonstrate a 16-channel demultiplexer for optical Orthogonal Frequency Division Multiplexed signals. The fabricated filter shows average cross-talk of <25 dB (best cross-talk of < 35 dB) for all channels.*

Introduction

Various techniques have been proposed to enhance the channel capacity to meet the demands of steadily increasing data rates. The Optical *Orthogonal Frequency Division Multiplexing* (OFDM) is considered as a promising candidate[1]. It is a multi-carrier modulation scheme in which the sub-carriers are overlapping in the frequency domain in such a way that the peak of one sub-carrier coincides with the zeros (minima of the side lobes) of all other sub-carriers, thus delivering high spectral efficiency and tolerance to fiber impairments due to the increased symbol duration[2]. The demultiplexing of such tightly packed sub-carriers requires a *Discrete Fourier Transformation* (DFT), because standard bandpass filters lead to a high OSNR penalty. A small form-factor, low power consumption, low cost and the ability to overcome the bandwidth limit of driving electronics provide the motivation of implementing DFT as a *Photonic Integrated Circuit* (PIC) using silicon photonics[3].

A 2-port *Multi-Mode Interference* (MMI) couplers[4] and *Arrayed Waveguide Grating Routers* (AWGRs)[5] have been used to implement DFT filters in silicon photonics. The MMI scheme uses a cascade of 2-port MZIs in a tree-like configuration. It lacks scalabilty as it requires a large number of coupling elements making the filter complex and susceptible to manufacturing-induced imperfections. Moreover, the AWGR approach makes tuning difficult as compared to the MMI approach, in which it is possible to tune one stage at a time to achieve the desired *sinc*-like transfer function. Using these approaches, demonstrations have been made to demultiplex up to 8 sub-carriers of an optical OFDM signal.

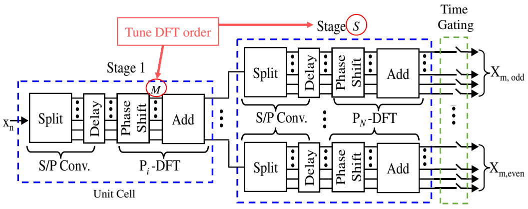

Fig. 1: Block diagram of an R_{th} order DFT filter using parallel-serial configuration

Previously we have demonstrated the use of a parallel-serial filter architecture that comprises a cascade of multi-arm MZI interferometers for signal processing applications[6]. Moreover, we have demonstrated the flexibility of this filter approach to demonstrate DFT using a micrometer-scale silicon photonics platform[7], which lacks active functions of high-speed modulation and photodetection.

As compared to other approaches, the use of parallel-filtering elements (i-e, multi-arm MZIs) reduces the complexity of filter implementation by reducing the number of coupling elements while still providing the flexibility to tune one stage at a time. In this work we demonstrate a 16-channel DFT filter fabricated on the 220 nm SOI platform. This can be a stepping-stone towards a fully integrated silicon photonics OFDM transceiver.

Filter Design

In the parallel-serial filter configuration, asymmetric MZIs with M arms are used as a basic building block (unit cell of the filter). For a filter with S stages, each stage performs the split, delay, phase shift and add operation. The *split and delay* operation is equivalent to a Serial-to-Parallel (S/P) conversion process and the phase shift and addition operation results in a *sinc*-like transfer function. Combining this transfer function with a gating (switching) function results in a DFT operation of the form:

$$X_m = \sum_{n=0}^{N-1} e^{-j2\pi\frac{mn}{N}}.x_n, m = 0, ..., N-1 \qquad (1)$$

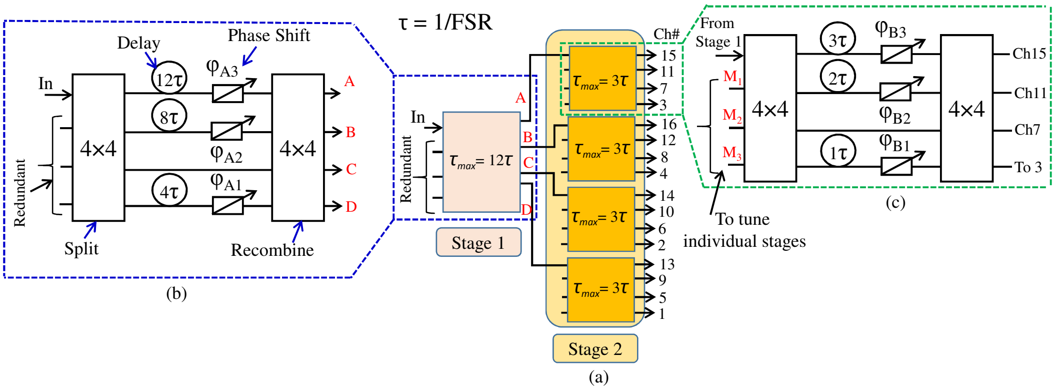

Fig. 2: (a) Schematic of the 16th order DFT filter, (b) shows the MZI of the first stage and (c) shows one of the four identical MZIs of the second stage. Each MZI of every stage comprises 4-port MMI couplers.

where *N* is the number of OFDM sub-carriers, X_m is the complex amplitude of m_{th} sub-carrier, x_n is the n_{th} equidistant sample of the complex incoming signal $x(t)$. Figure 1 shows a DFT filter of order R comprising S stages using parallel filtering elements (i-e. M-port MMI couplers). The DFT order R can be scaled by either increasing the number of stages S or by increasing the order M of the parallel-filtering elements.

In Figure 2(a) - the middle figure- shows the schematic of the 16-channel DFT filter. The filter consists of two stages. Both stages consist of 4-arm asymmetric MZIs using 4-port MMI couplers. The first stage, shown in Figure 2 (b), has only one MZI. It has a maximum delay $\tau_{max} = 12\tau$. The second stage consists of four 4-arm MZIs, each connected to one of the outputs of MZI of the first stage. Each MZI of the second stage, as shown in Figure 2 (c) has $\tau_{max} = 3\tau$. Here τ determines the *Free Spectral Range* (FSR) of the filter, which is given by $FSR = \frac{1}{\tau}$. The total delay of 15τ from the two stages determines the minimum spacing between the OFDM sub-carriers to be demultiplexed. In both stages the order of the delay lines is re-arranged and an appropriate phase shift is applied to achieve the DFT transfer function. Figure 4 (dotted green line) shows the theoretical response of a 16th order DFT filter considering loss-less waveguides without any phase errors and with ideal MMI couplers without any imbalance or phase inaccuracy. The circuit level simulation is performed by VPI Transmission Maker version 9.7. The FSR of the simulated filter is 400 GHz to demultiplex 16 optical OFDM sub-carriers with 25 GHz of channel spacing (the zeros of the side lobes of the filter are 25 GHz apart).

The simulated device is fabricated by using imec's open access passive silicon photonics technology platform. Shallow etched MMI couplers with less than 5° phase inaccuracy have been used. Figure 3 shows the microscopic image of the fabricated device. For tuning the phase shift on the delay lines, thermo-optic tuning produced by micro-heaters is used. The device has a total size of 2.5 mm × 1.5 mm but it can be further reduced by a more optimized layout.

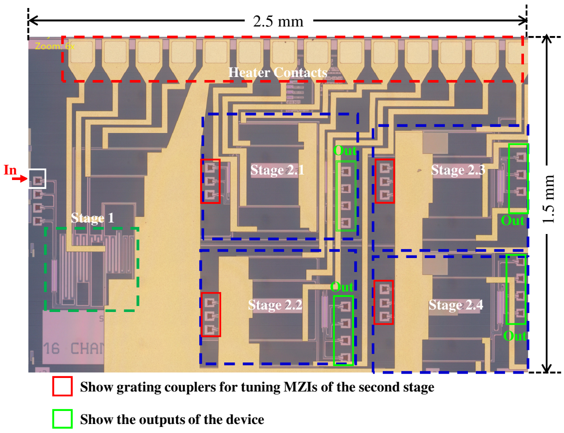

Fig. 3: Microscope image of the fabricated device.

The device is measured at a temperature of 20°C by placing it on a temperature controlled carrier. This prevents any spectral shift due to temperature variation on the chip. The measurements are performed by using TE polarized light. To obtain the *sinc*-like transfer function of the filter, appropriate phase shifts are applied on the delay lines. Figure 4 shows the measurement result for one of the channels of the measured device and its comparison with the ideal response of the device. A very good match is achieved between ideal and the measured device. The alignment of the simulated filter zeros and measured filter zeros show the orthogonality of the measured filter response. This high orthogonality is highly desirable for demultiplexing of optical OFDM sub-carriers without inducing OSNR penalty.

The measured FSR of the filter is 401.7 GHz at a wavelength of 1550 nm. The extinction ratio

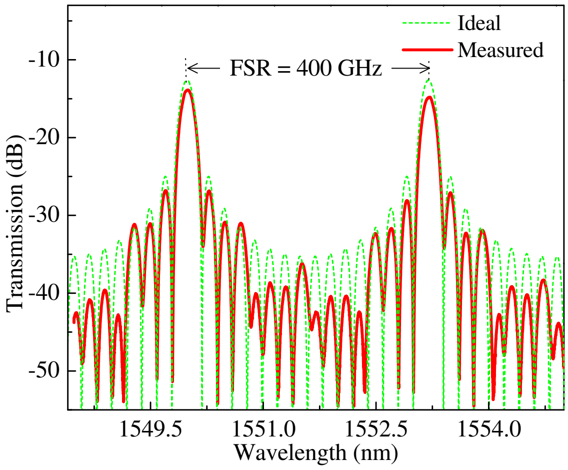

Fig. 4: Measured response for the fabricated filter (red solid line) and its matching with the ideal filter response (green dotted line).

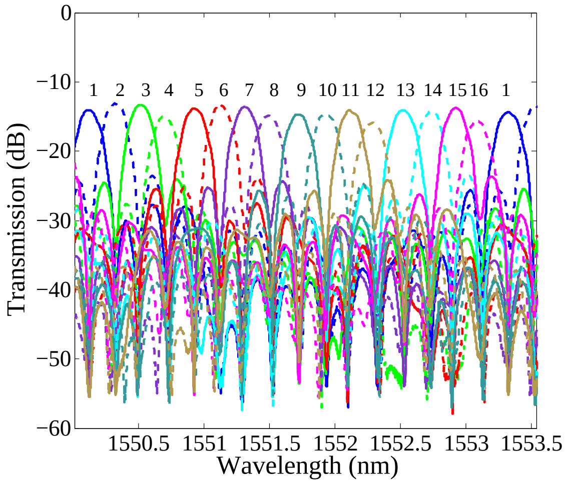

Fig. 5: Measured response for all 16 channels of the optical OFDM demultiplexer.

varies from 24 dB to $>$ 40 dB. The device has a fiber to fiber insertion loss of $\approx$ 13.5 dB with $\approx$ 11 dB originating from the focusing grating couplers for out-of-plane coupling into a cleaved standard single mode fiber. For all channels the side lobes are suppressed by $\approx$ 11 dB. Figure 5 shows the measured transmission response for all 16 channels of the device. These measurements are performed for only one settings of the phase shifting elements while ensuring that all channels provide sinc-like transfer function. Figure 6 shows the cross-talk of all channels when measured from the peak transmission wavelength of a channel. The average cross-talk for all channels is > 25 dB. A degraded cross-talk is observed between the adjacent channels with an average cross-talk of $\approx$ 18 dB. The worst cross-talk of $\approx$ 14.5 dB is measured between channels 11 and 12. The non-adjacent channels have shown much higher cross-talk values of $>$ 35 dB. To determine the performance of the filter for demultiplexing of 16x25 GHz optical OFDM sub-carriers the cross-talk of the filter is measured on a 0.2 nm grid. The worst cross-talk in this case has degraded to $\approx$ 14 dB. The average cross-talk of neighboring channels has degraded by only 1.5 dB. Moreover, the average cross-talk for all channels has not degraded when measured on a 0.2 nm grid.

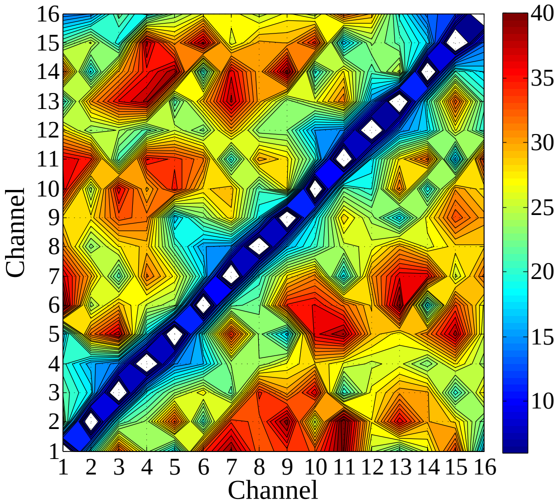

Fig. 6: Measured cross-talk at the peak transmission wavelength of the filter channels.

Conclusions

A 16-channel optical OFDM demultiplexer is demonstrated in a 220 nm Silicon-on-Insulator platform using the parallel-serial filter approach. The realized device shows good match with simulation results as well as high orthogonality among 16 channels and better than 25 dB of average cross-talk for all channels.

References

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