Silicon Photonic Devices for Advanced Modulation Formats

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Abstract—In modern optical transmission systems the traditional on-off keying (OOK) is replaced by advanced modulation formats like higher order phase shift keying (mPSK) combined with coherent detection. This requires more complex receivers with additional integrated optical components to retrieve phase and amplitude information of the optical signal.

The most important building blocks and possible realizations for compact and low loss optical front ends are presented.

Index Terms—Si Photonics, Photonic Integrated Circuits, Advanced Modulation Formats, Receiver Front-End.

1. INTRODUCTION

Optical transmission systems applying advanced modulation formats in their sub-channels are the most promising candidates for the next generation optical networks [1]. Data rates of 100 Gbit/s per channel are already demonstrated, e.g. using differential quaternary phase shift keying (DQPSK) [2].

Also coherent detection at the receiver side revives, since the required extensive electrical post processing becomes nowadays possible with commercially available Silicon CMOS technology [3]. Thus a common silicon platform for both electrical and optical integrated circuits is highly desirable. In fact, due to its low absorption and high refractive index, Silicon is dedicated to guide light at infrared wavelengths, i.e. 1.5 μm, very efficiently. This allows realizing all key building blocks for optical front ends in Silicon, except the photodetector. The detector problem is solved by using pure Germanium layers as absorber material [4].

In the next sections, a typical system architecture is presented and solutions for the main building blocks are discussed in more detail.

2. RECEIVER ARCHITECTURE

Several building blocks are needed at the receiver side for the optical processing of the input signal. The signal is transmitted by an optical fiber. Thus the first step is an efficient coupling of the fiber and the planar waveguide on chip. A simple butt coupler at the edge of the chip has high losses due to the different numerical apertures and a functional test of the circuit is only possible after final dicing of the wafer. Grating couplers at the surface allow vertical coupling at arbitrary locations and offer better coupling efficiency. They are described in more detail in section 3.1.

In order to improve the spectral and power efficiency of optical communication systems, both orthogonal polarizations – transversal electric (TE) and transversal magnetic (TM) – are used in the advanced optical modulation formats. As each polarization state can carry separate data streams on the optical fiber, a polarization beam splitter (PBS) has to be used at the receiver side to separate both states. So each data stream can be recovered apart. In Fig. 1, only one section is shown for simplicity.

If the input signal is differentially encoded, an additional delay line with one bit delay is needed. For coherent detection, a local oscillator is required. Both, data signal and local oscillator signal, are fed to a 90° optical hybrid to convert phase information to an intensity distribution that can be detected by photodiodes at the outputs of this hybrid. To increase sensitivity, balanced detectors are used. Their electrical output signals correspond to the I and Q components of the transmitted signal. Further electrical signal processing becomes necessary to account for e.g. dispersion effects and noise. Also the effects of phase and frequency drift of the local oscillator can be mitigated by post processing of the electrical data.

3. MEASUREMENT SETUP FOR PIC CHARACTERIZATION

In Fig. 2, the measurement setup used to characterize the Si based PICs is depicted. The polarization of the CW signal from a 1310 nm or a tunable 1550 nm laser is adjusted via a polarization control. The SMFs are placed above the chip, their tilt can be tuned manually while the xyz-position is set with the help of piezo actuators.
4. BUILDING BLOCKS FOR RECEIVER FRONT-END

4.1. Grating Coupler

Grating couplers serve as the interface between single mode fibers (SMF) and chip. The light arriving vertically is deflected by the grating and coupled to the planar waveguide. Grating parameters such as grating period $g$, fill factor $dc$ and groove depth are essential for good performance. A standard grating coupler design for a wavelength of 1550 nm is proposed by imec (see e.g. [5]). The process used is available via ePIXfab and comprises a 248 nm UV lithography and two Si/etch steps, one full and one partial.

Additionally couplers with varying grating period $g$ and varying fill factor $dc$ are examined to determine the impact of the single parameters. The measurement results are shown in the following Fig. 3 - 4. Also grating couplers specially designed for a wavelength of 1300 nm are investigated.

According to Fig. 3 and Fig. 4, the wavelength at which maximum coupling efficiency occurs shifts to higher values for increasing grating period $g$. The same holds true for increasing the fill factor $dc$. Note that the angle of incidence is $13^\circ$ in respect to the surface normal. The angle of incidence is another important parameter to achieve optimum coupling efficiency.

In Fig. 5, the procedure to determine the optimum value of the angle of incidence is illustrated: the incident angle is kept fix at an estimated value, $15^\circ$ in this case, and the output angle is swept. The output angle at which maximum transmission is found ($20^\circ$ in the given example) is also the best input angle, as the light path is reversible in this symmetrical structure.

Maximum coupling efficiencies of 0.37 (-4.3 dB) at 1550 nm and 0.4 (-4.0 dB) at 1300 nm were shown for grating couplers. These values are well above the coupling efficiency of a simple butt coupler for which coupling losses are usually higher than 20 dB [6]. The losses could be decreased by using e.g. 2D inverted tapers on the SOI substrate. This can reduce the butt coupling losses to 12 dB (measured) and 4.5 dB (simulated) [6], which is comparable to the results presented in this paper. However, one important drawback of the lateral edge coupling still remains: the structures cannot be tested until the wafers are diced.

Since the grating couplers are polarization sensitive, these structures can be designed to act also as polarization splitters, as reported e.g. in [7], so that chip footprint can be reduced further.

4.2. Polarization Beam Splitter

To increase the capacity of transmission systems, a dual polarization (DP) scheme is applied. In general the polarization is split at the receiver side by an external PBS, outside the chip. Polarization sensitive grating couplers allow integrating this function together with the fiber-to-chip coupling. There are other methods such as directional couplers [8], micro racetrack resonators [9], metal-loaded embedded waveguides [10], etc. In addition, photonic crystals can be
interesting candidates to separate polarizations, as they are very compact in size.

Fig. 6 shows an integrated photonic crystal polarization beam splitter that was designed at INT and realized in SOI technology [11].

![Fig. 6: Polarization beam splitter using a photonic crystal structure. Left side: microscopic picture with input and output waveguides, right side: SEM picture of PC](image)

The signal enters a photonic crystal section that is tilted in a plane parallel to the surface. As the wavelength is within the pass band of the photonic crystal, incident light is refracted. The transmission properties of this 2-dimensional photonic crystal depend on the polarization of the incident wave, thus the refraction is different for the two SOP. They are separated by a small distance and coupled to the output waveguides 1 and 2 respectively.

![Fig. 7: Simulation and measurement results of a photonic crystal polarisation beam splitter. The transmission of the two ports is shown for TE and TM input polarization.](image)

At output 2 the transmission for TE is better than -15 dB and TM is suppressed by 11.1 dB at a wavelength of 1520 nm. The difference between simulation and measurement, which is basically a shift in wavelength, results from geometrical deviations of the targeted dimensions.

### 4.3. Optical 90° Hybrid

The 2x4 optical 90° Hybrid is required for both coherent detectors as well as for DQPSK direct detectors. Basically it is a device with two input waveguides and four output waveguides. The input fields interfere at the output waveguides with a constant phase relation $\phi_0$ plus $0, \pi/2, \pi$ and $3\pi/2$, depending on the position of the output waveguide. Therefore it is possible to retrieve the I- and Q-component of the transmitted signal and to detect m-PSK coded symbols.

There are different options to realize such a device [1], e.g. by employing four 3-dB-couplers and a phase shifter between two of the couplers. This solution suffers from the variation of the phase shifter that leads to IQ imbalance as long as no active loop control is employed. The total area covered by the 3 dB couplers is also a drawback.

A multimode interference (MMI) coupler which is based on the self-imaging effect offers the desired phase relations inherently. Furthermore, MMI based 90° hybrids are broadband and therefore can cope with wavelength multiplexed signals.

Due to the high index contrast of the SOI material system small input and output waveguides and consequently a very compact multimode section can be used. Figure 8 shows a simulation result of a MMI with only one input signal (fed from the lower left input waveguide). The input field is split equally to the four outputs. This is a very compact 1-to-4 splitter.

![Fig. 8: Intensity contour plot with one input signal at the lower left. The light is equally coupled to the four output waveguides. (size is not to scale)](image)

In Fig. 9 simulation results of a structure with two input signals are shown. One represents the phase modulated signal, the other one is the reference signal of the local oscillator. If properly designed, both signals interfere at the output waveguides with a constant phase difference of $\phi_0 + m \cdot \pi/2$ with $m = 0, 1, 2, 3$.

In this simulation the phase relation between the two signals is chosen in a way that the arbitrary angle $\phi_0$ becomes zero. In a real system, a phase
controlling element in front of one input can be used to establish exactly this condition. However this may not be necessary when using digital signal processing to estimate the phase $\varphi_0$.

By new designs of e.g. photonic crystal structures a further reduction of device area is achievable. The use of MMI couplers also saves chip area and allows compact designs for receiver front ends for advanced modulation formats. With the available CMOS technologies the complete integration of both optical and electronic functions with high complexity and for very high data throughput becomes possible.

REFERENCES