Use of silicon photonics wavelength multiplexing techniques for fast parallel readout in high energy physics

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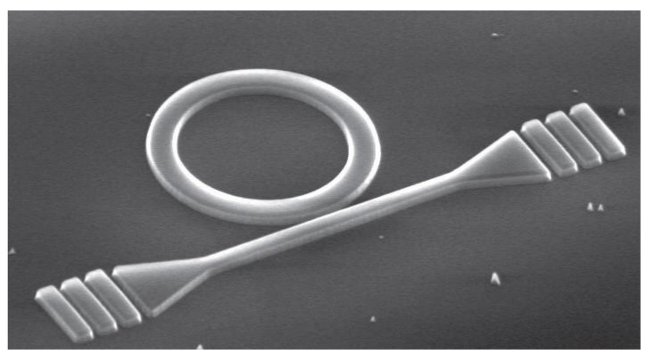
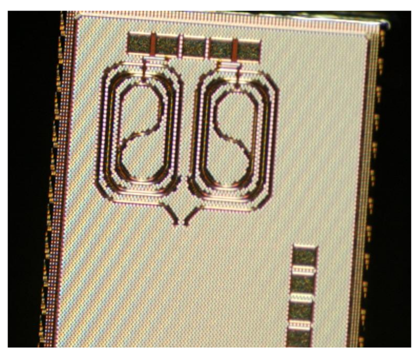
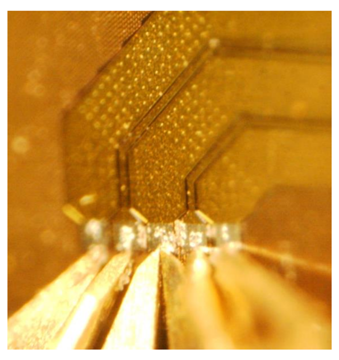
ABSTRACT – Silicon pixel is a widely used detector technology in many fields of science and applications, from particle and nuclear physics experiments to medical physics. A pixel detector is typically composed of : a highly segmented silicon sensor die connected with "bump bonding" technology to a readout ASIC. Typical parameters of a readout ASIC are: 50x50 pixels, 300x300 um per pixel and time resolution at the level of 100 ps. We propose to use wavelength multiplexing on a silicon photonics circuit for highly segmented pixel detectors readout.

Silicon Photonics

Silicon photonics is a rapidly emerging field in research and technology thanks to:
- strong optical confinement of light due to its high index contrast with most materials;
- compatibility with cheep highly integrated CMOS (Complementary Metal-Oxide-Semiconductor) processes.

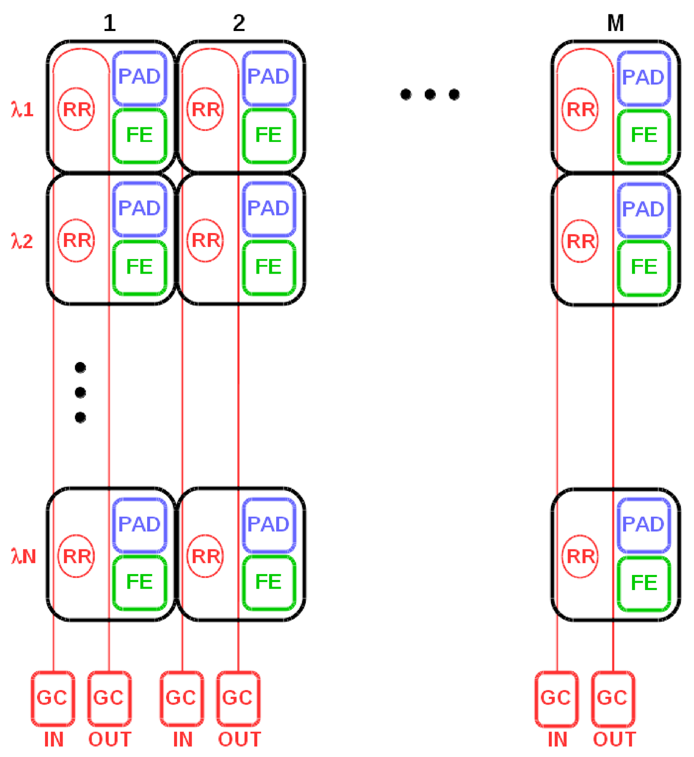
The basic structures used in integrated photonics systems are:
- Bragg grating couplers used to feed laser light in and out of the photonics circuits;
- tapered or linear waveguides used to transport laser light inside the photonic integrated circuits;
- Mach-Zehnder Interferometers (MZI) and Ring Resonators (RR) used to implement optical signal modulation.

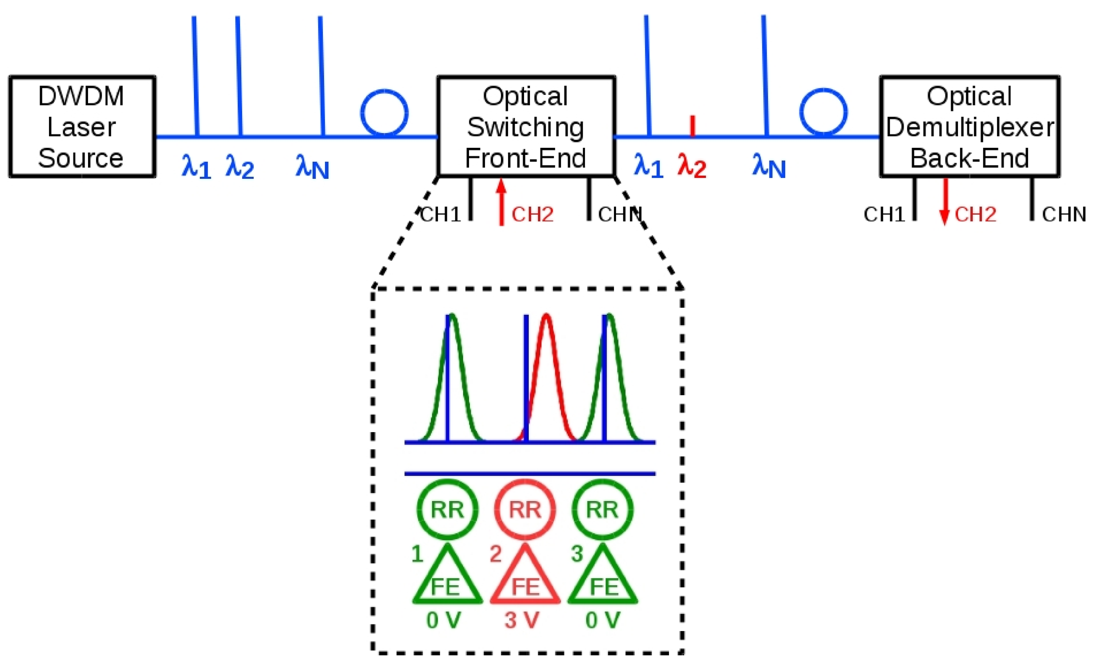
Optical modulation is obtained in silicon photonics circuits via electro-optical effect (plasma dispersion). In a MZI the electro-optical effect is used to modulate the interference condition of the two branches of the interferometer, while in a RR it is used to control the resonance condition of an optical ring coupled to an optical waveguide.

Fast parallel readout concept

Each element (channel) of the front-end ASIC will be composed of an amplifier and shaping circuit controlling a ring resonator tuned to its peculiar optical wavelength and coupled to a common optical line.
At the arrival of a particle, the pulse current produced by the detector is amplified and shaped by the front-end electronics and used to drive the corresponding ring resonator to a new resonance condition modifying the optical fingerprint of the RR array in a peculiar way specific of each channel.
Many front-end channels can be encoded and transmitted on the same common optical line and subsequently decoded by the back-end optical demultiplexer chip. In this back-end chip, a photodiode performs the optical-to-electric signal conversion.



A silicon photonics parallel readout wavelength multiplexing system will be composed of: a front-end optical switching ASIC,one or more optical fibers, an optical back-end demultiplexing ASIC.



The main parameters of each Ring Resonator are:
- diameter 80-100 um;
- Q-factor 10^4;
- Full Width Half Maximum (FWHM) 300 pm (370 GHz);
- Free Spectral Range (FSR) is 10 nm;
- linear tunability 20 pm/V.

Given the FSR and the FWHM, N = 16 Ring Resonators can be conservatively coupled to the same optical line without wavelength overlap (with the perspective to increase this number with more developments).

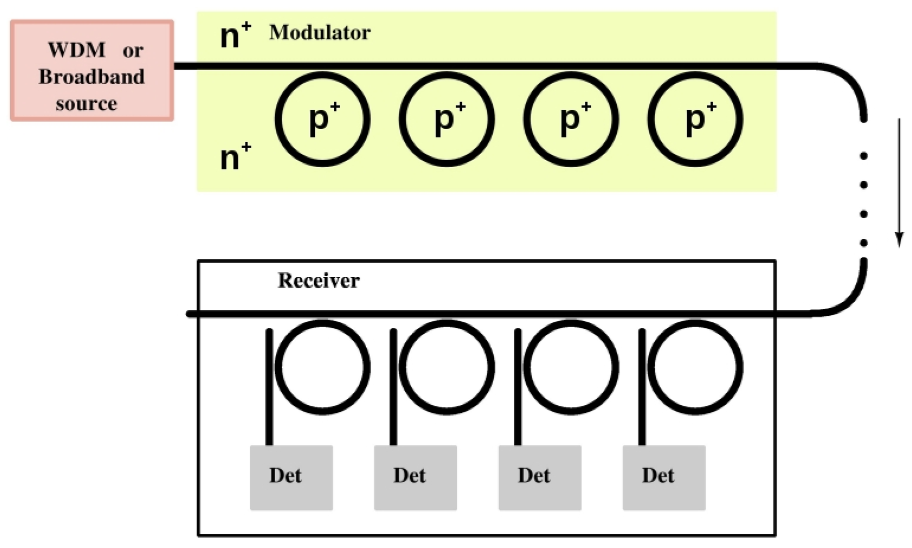
Wavelength Multiplexing Technology

Optical wavelength division multiplexing (WDM) is a telecommunication technique originally introduced at the end of 70s aiming at increasing the bandwidth of optical fibers communications. Several signals can be transmitted on the same optical fiber modulating different laser sources (at different wavelength) each one corresponding to a specific communication channel.

A WDM system is composed of:
- two or more transceivers, one for each channel, which translate the electrical signal to optical signal at a given wavelength and vice versa;
- a multiplexer which combines several optical signals at different wavelengths and sends them on a single optical fiber;
- a demultiplexer which splits the optical signals at different wavelengths in different optical fibers for separate readout.

Several WDM technologies were developed along the years: normal (WDM), coarse (CWDM) and dense (DWDM). WDM technology uses two different wavelengths centered in the second and third transmission windows (1310 and 1550 nm). With CWDM up to 18 optical wavelengths are multiplexed in the second and third transmission windows.In DWDM technology several channels are multiplexed in the C-band transmission window (1530-1565 nm).

Typical commercially available DWDM systems implement 40 channels at 100 GHz spacing or 80 channels at 50 GHz spacing. High-end more advanced and expensive systems can implement up to 160 channels with 25 GHz spacing.Typical parameters of a transceiver for an 80 channels 50 GHz spacing system are: power 0-5 dBm, line width at -20 dB 0.3 nm, maximum fiber length without amplification 80-120 km.



Wavelength division multiplexing can be obtained using cascaded microrings sharing a common bus waveguide with individual drop waveguides.

One of the keys point for the successful operation of this new readout concept is the choice of the laser source.
A suitable source can be implemented with a DWDM multiplexer (centered on the 50 GHz ITU-T DWDM grid) together with a commercially available Distribute Feedback Lasers (up to 14 dBm output power with a laser line width < 50 MHz)) or a standard DWDM transceiver (up to 5 dBm output power) for each input laser line.

Silicon Photonics Technology

SG25H4_EPIC technology parameters:
- SiGe:C (BiCMOS) technology especially suited for applications in the higher GHz bands (up to 190 GHz transit and up to 220 GHz oscillation frequencies);
- 0.25 µm CMOS process with Nmos, Pmos and passive components;
- local Silicon On Insulator process for photonic modules.

Applications

This proposed parallel readout system has many advantages compared to a traditional architecture:
- no complex, power consuming digital electronics implemented on the detector readout ASIC allowing on-detector power consumption, interference and complexity reduction;
- the intrinsically parallel architecture allows fast readout, mandatory in many experiments and applications.

All the applications requiring a low noise, low power front-end with high electromagnetic interference immunity will benefit form this proposed optical multiplexing readout scheme:
- particle and nuclear physics experiments with fast timing detectors (e.g. RPCs, MPGDs, silicon detectors);
- advanced medical imaging instruments (e.g. PET/MRI and SPECT/MRI);
- space instrumentation.