Programmable Photonic Processor

Literature review and simulations

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Article Summary

31/07-07/08

Introduction

- Programmable photonic circuits manipulate the flow of light on a chip by electrically controlling a set of tunable analog gates connected by optical waveguides.

- The limitations by complexity in photonic circuits can be mitigated by using compact footprint, modular and scalable fabrication methods of integrated photonic circuits.

- Integrated Microwave Photonics (MWP) allowed a dramatic reduction on size and complexity but lack on reconfigurability.

- Creating a circuit that can fulfill numerous applications, mitigate several application cycles and long fabrication costs and time.

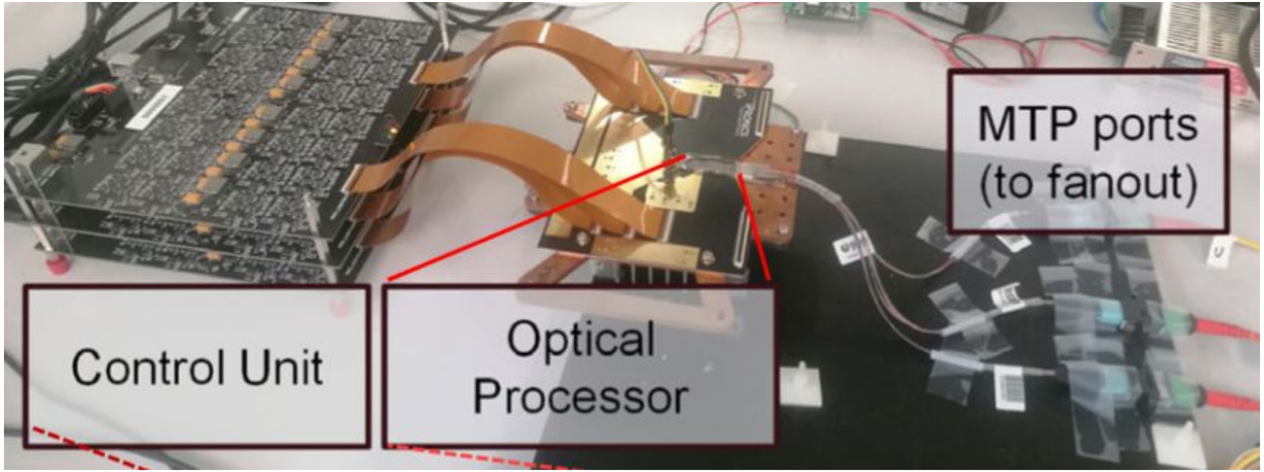
- This processor can work in frequency ranges of up to 100 GHz featuring power consumption values of a few Watts.

Reference: General-purpose programmable photonic processor for advanced radiofrequency applications

Results

The general-purpose photonic processor presented in this work aggregates:

- The optical layer;
- The control layer;
- The software layer;



Optical Layer

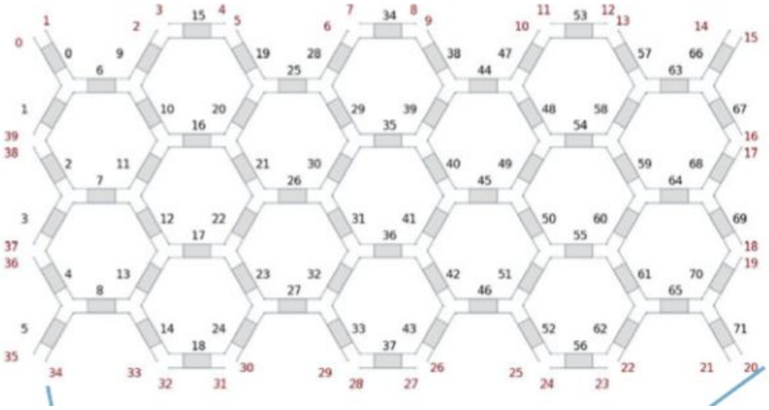
In this layer we have:

- 72 Programmable Unit Cells (PUC) in flatted hexagonal mesh topology;

- Optoelectronic monitoring unit array;

- Four high-performance filters;

- This chip is connected optically through a fiber array with 64 ports, from where 28 are routed to the mesh core and electronically through a wire bounding interconnection to a Printed Circuit Board (PCB).



Optical Layer

The chip is optimized for C-band operation. Mesh core has 40 outputs, 12 connected to on-chip high performance blocks.

- The insertion loss and efficiency are 0.48/PUC and 1.3mW/π.

- The length and basic delay unit are also characterized as 811 um and 11.2 ps.

- Propagation losses are measured between 1.5 and 2.5 dB/cm for different waveguide widths and dies.

- Fiber-chip coupling loss employed are 3dB loss per facet.

Control and Software Layers

In this layers we have:

- 304 on-chip phase actuators;

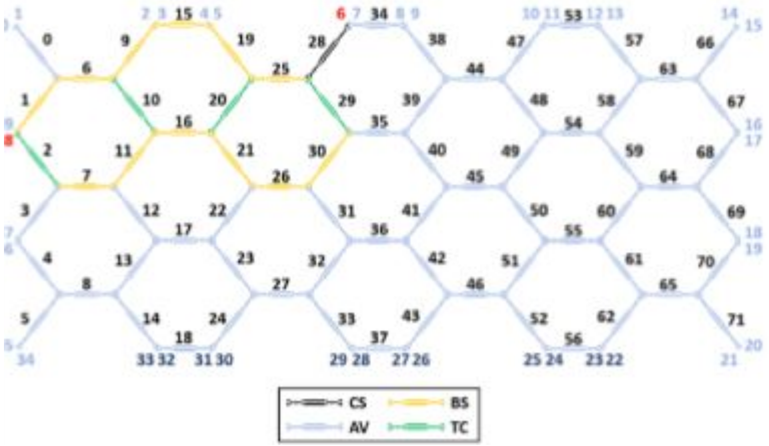
- 40 on-chip photo-detectors;

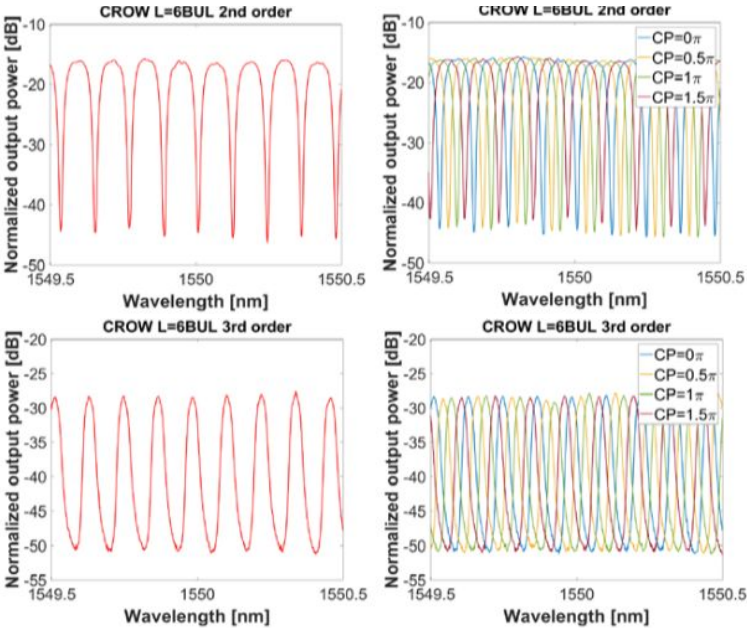
- An software running in the LU with overall operation and can get instant data. The reconfiguration time of the system is 15-90ms.

- The software layer includes the back-end functions necessary to maintain the chip temperature stable, drive and read from the photonic electro-optic components;

CROW Filter

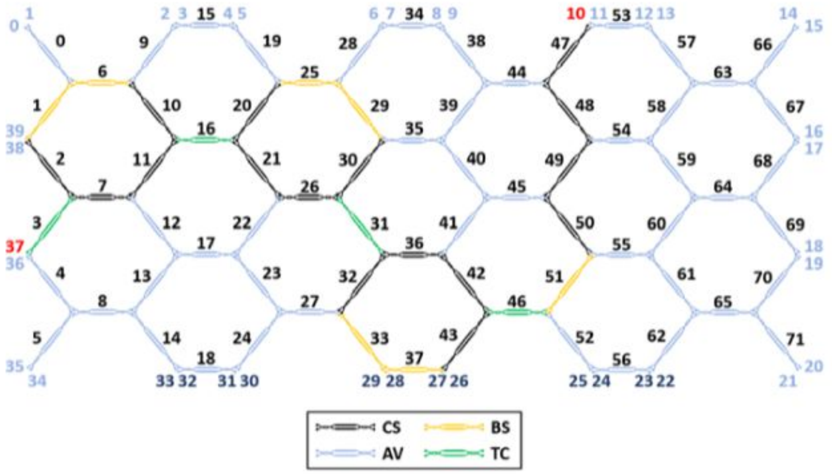
This example is an Coupled Resonant Waveguide Filter (CROW), featuring three coupled-ring cavities of 6 Basic Unit Length (BUL), his filter has two complementary outputs representing the reflection and transmission of a resonant filter. (CS: Cross State switch, BS: Bar State switch, TC: Tunable Coupler, AV: available)

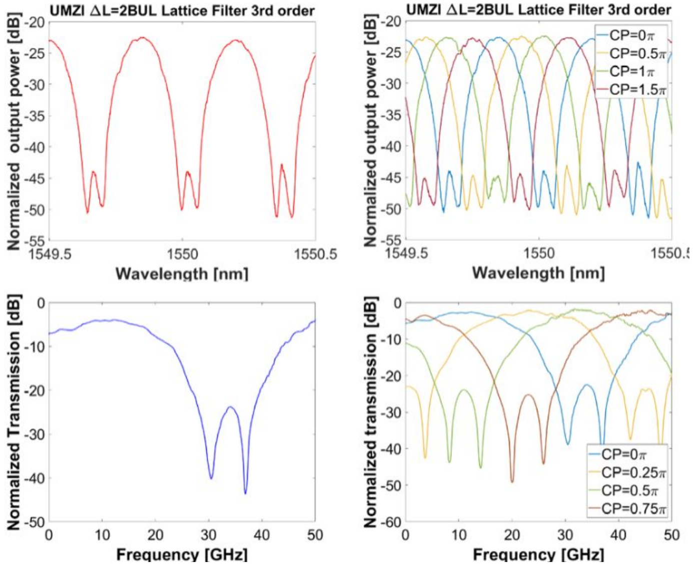




UMZI lattice filter

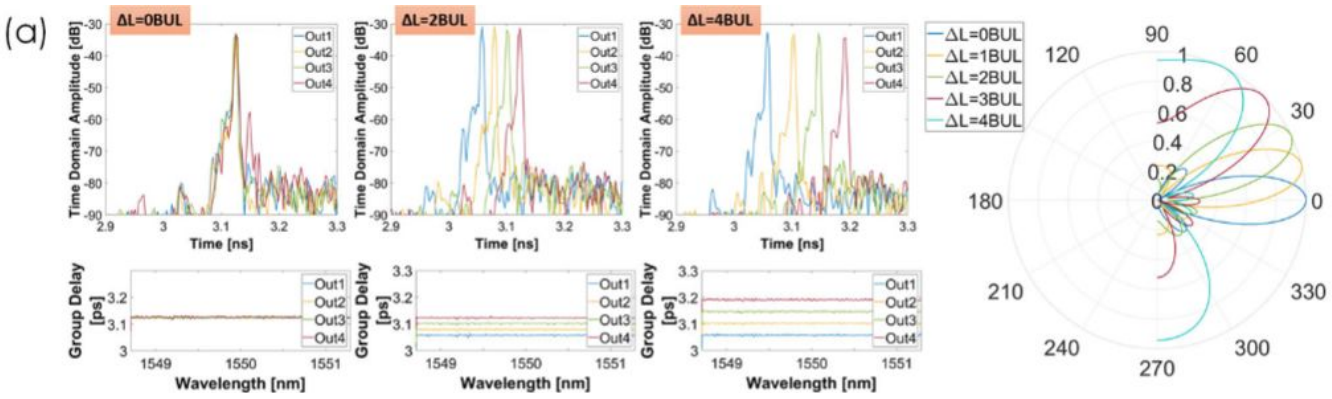
This example uses a 2BUL path imbalance to create an third-order unbalanced Mach-Zehnder Interferometers (UMZI) lattice filter .The filter has an 21dB extinction ratio and 44.95 GHz FSR with the bandpass position fully tunable.





Tunable delay lines and beamforming

The processor to enable a four-element beamformer capable of pointing up to 9 angles (4 positive, broadside and 4 negative in a −55° to 55° range where ΔL = 1 BUL→θ = 13.7°, ΔL = 2 BUL→θ = 27.4°, ΔL = 3 BUL→θ = 41.25°, ΔL = 4 BUL→θ = 54,9° and a similar reversed configuration provided the negative pointing angles.



Discussion

- Operation frequency ranges in the 15 to 45 GHz band have been demonstrated but even higher frequency ranges can be achieved by reducing the BUL.
- The Current value of 811 μm can be lowered to around 200 μm thus reaching beyond 200 GHz operation bandwidth.
- Current value of around 0.48 dB/PUC can be lowered to figures around 0.1 dB/PUC.
- We estimate that the current figure of 1.91 actuators per mm2 chip can be upgraded to 10 actuators per mm2.
- The Power consumption of around 1–2 mW/π per phase shifter already achievable, we envisage full cores with over one thousand operating PUCs consuming 1 watts or less.

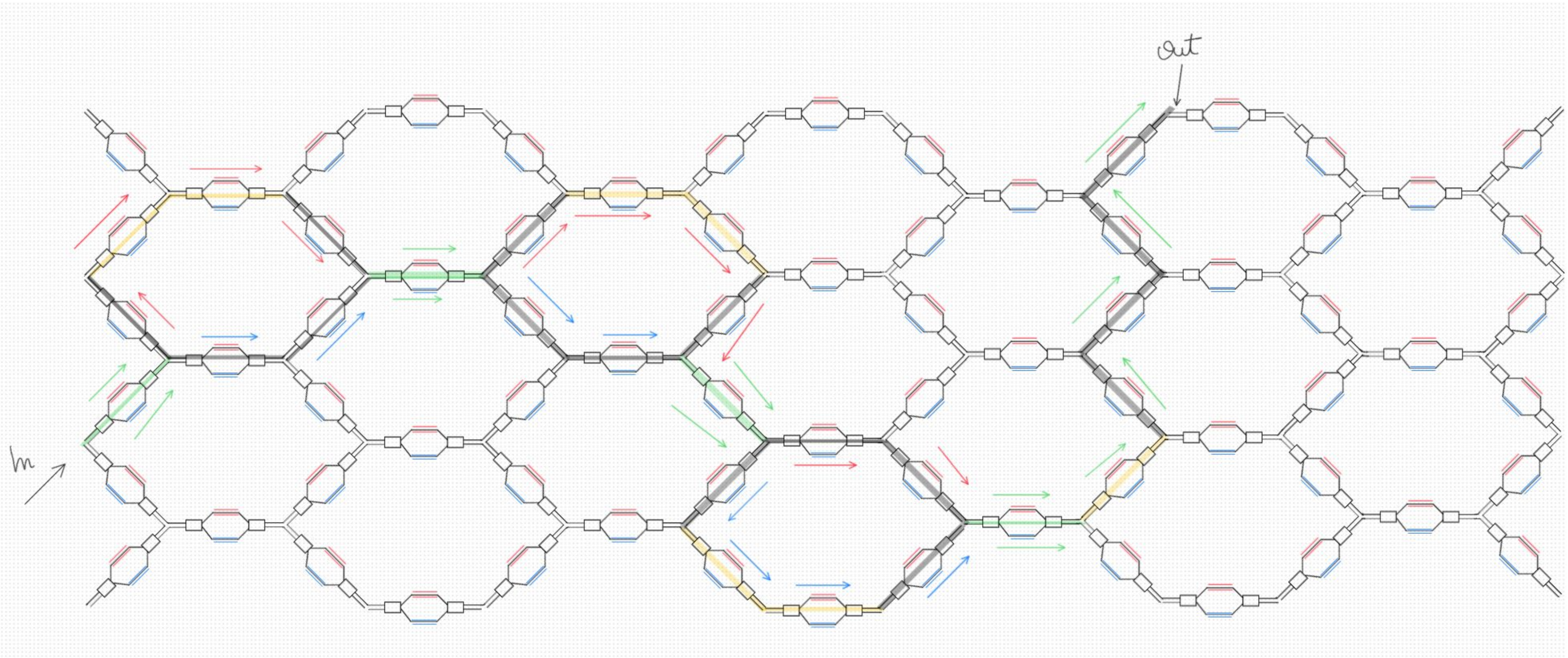
Methods

- The photonic core was fabricated using 130 nm lithography process in SOI wafers with a 220-nm thick silicon overlayer and a 3-μm thick buried oxide layer.
- Germanium on silicon is employed for on-chip photodetection.
- A Printed Circuit Board (PCB) is also attached to the copper structure and a wire bonding process was used to provide electrical connections between the die and the PCB.
- A fiber array with a pitch distance of 127 μm was fixed to the on-chip edge coupler array of the die by active alignment and epoxy.

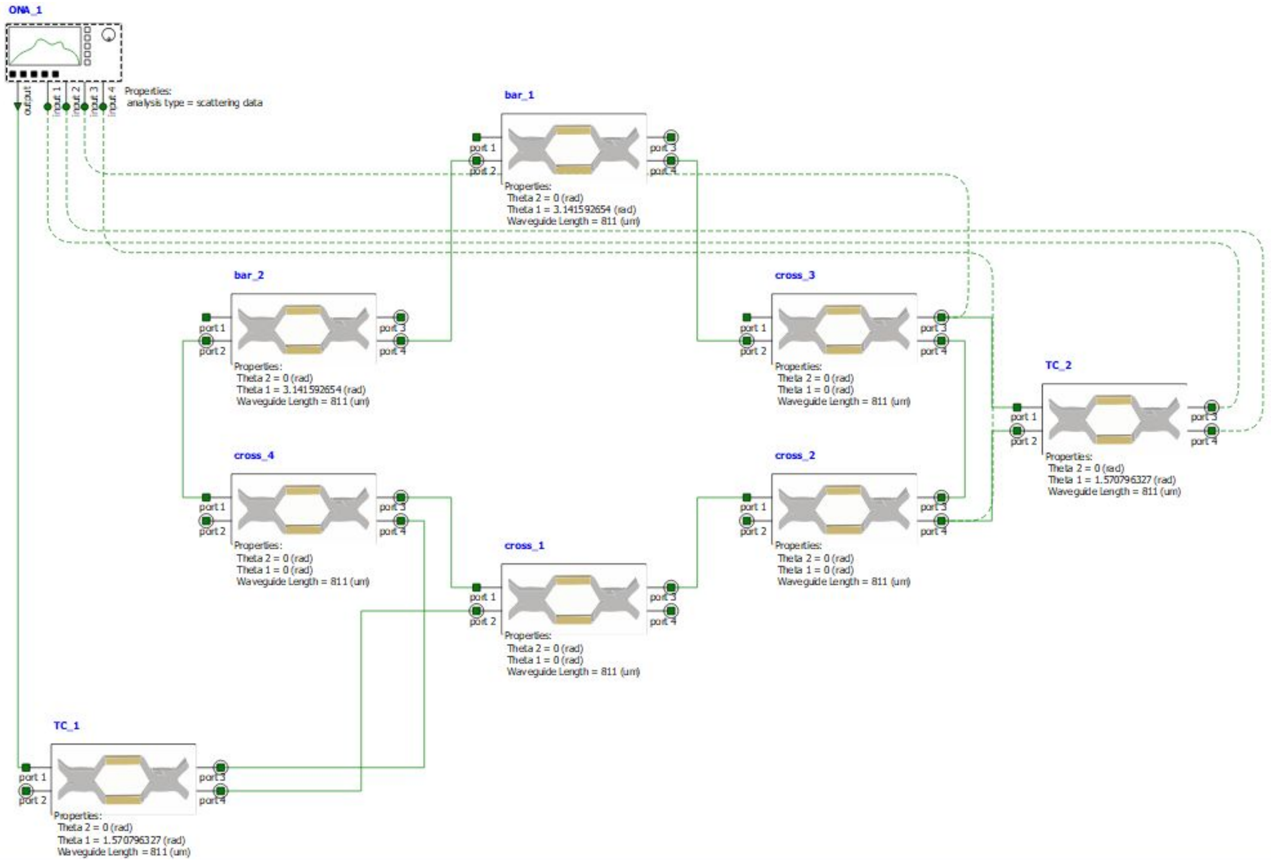
UMZI Simulation

06/08-20/08

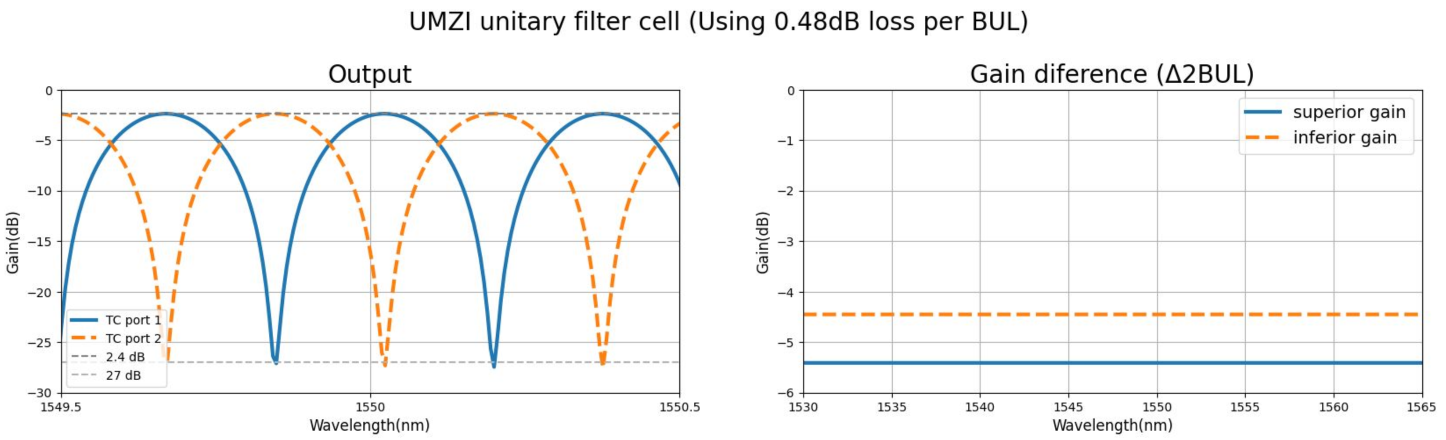
UMZI Schematics

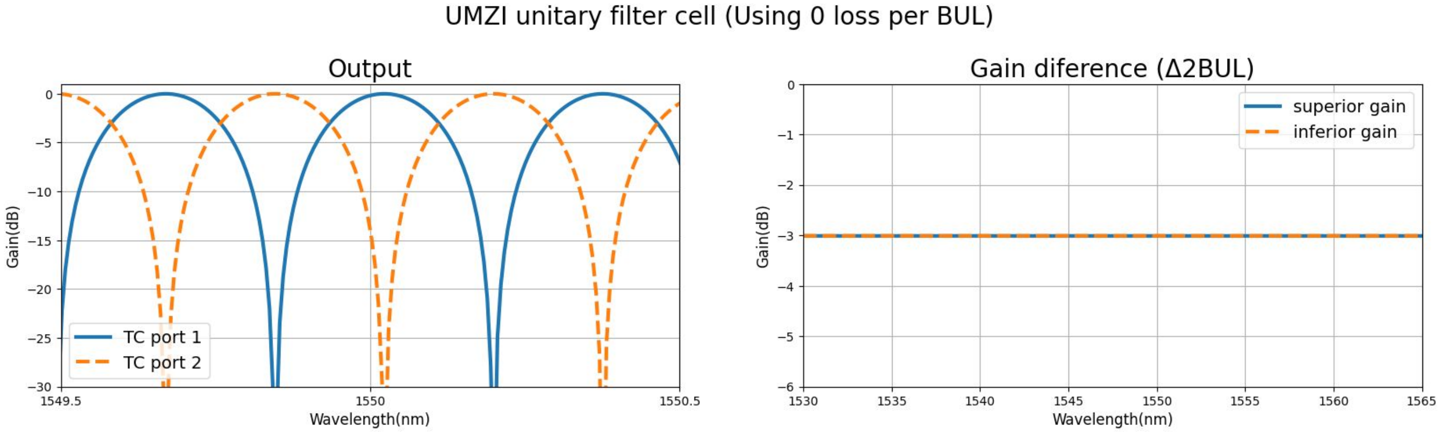


UMZI unitary cell INTERCONNECT



UMZI unitary cell INTERCONNECT

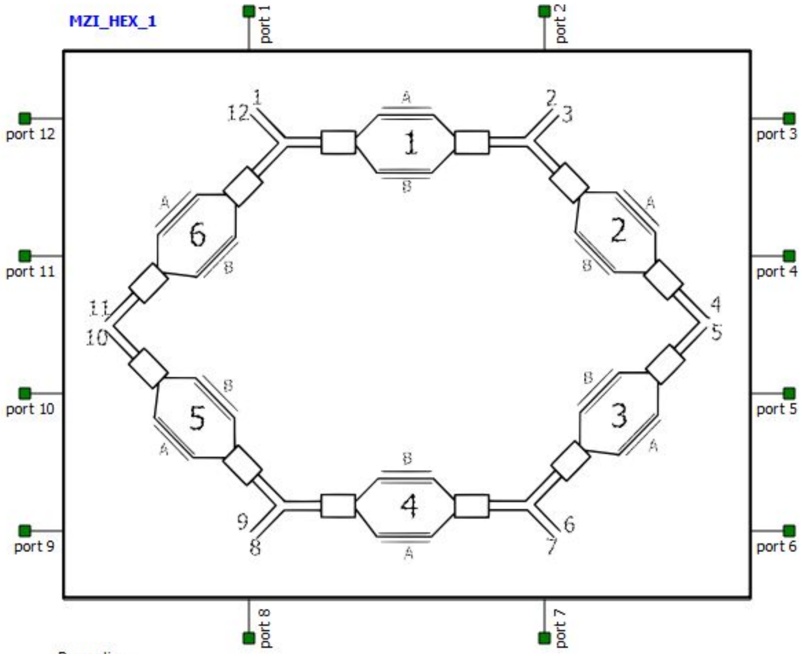




Testing Bar differences and MZI Hex generation

20/08-03/09

MZI Hex generation



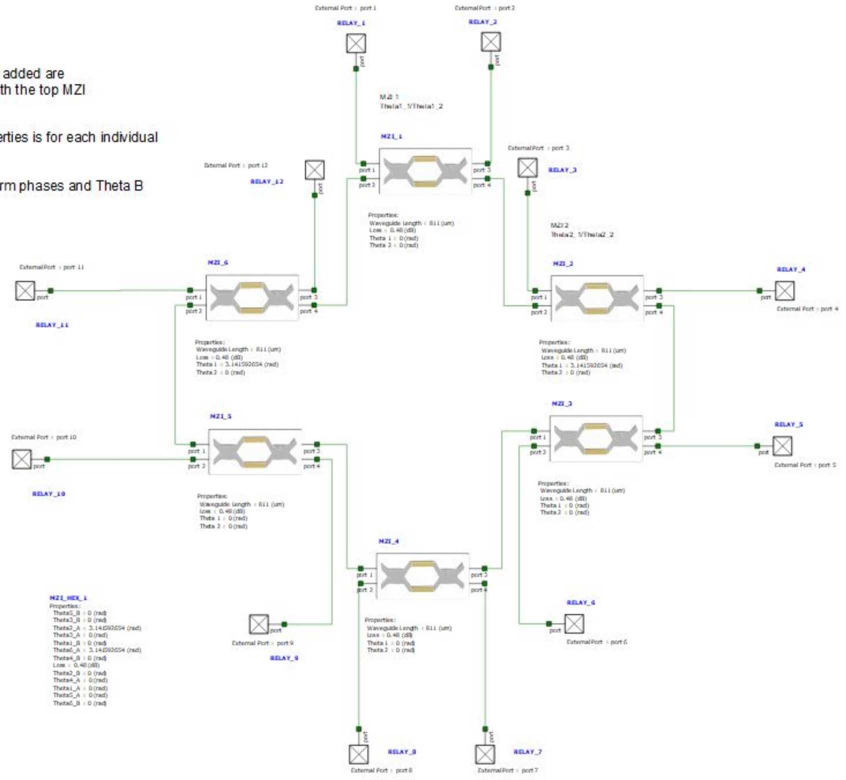
Properties:
Theta5_B = 0 (rad)
Theta3_B = 0 (rad)
Theta2_A = 3.141592654 (rad)
Theta3_A = 0 (rad)
Theta1_B = 0 (rad)
Theta6_A = 3.141592654 (rad)
Theta4_B = 0 (rad)
Loss = 0.48 (dB)
Theta2_B = 0 (rad)
Theta4_A = 0 (rad)
Theta1_A = 0 (rad)
Theta5_A = 0 (rad)
Theta6_B = 0 (rad)

MZI Hexagonal Cell.

Parameters and ports added are disposed clockwise with the top MZI beeing the first.

The Loss set on properties is for each individual MZI.

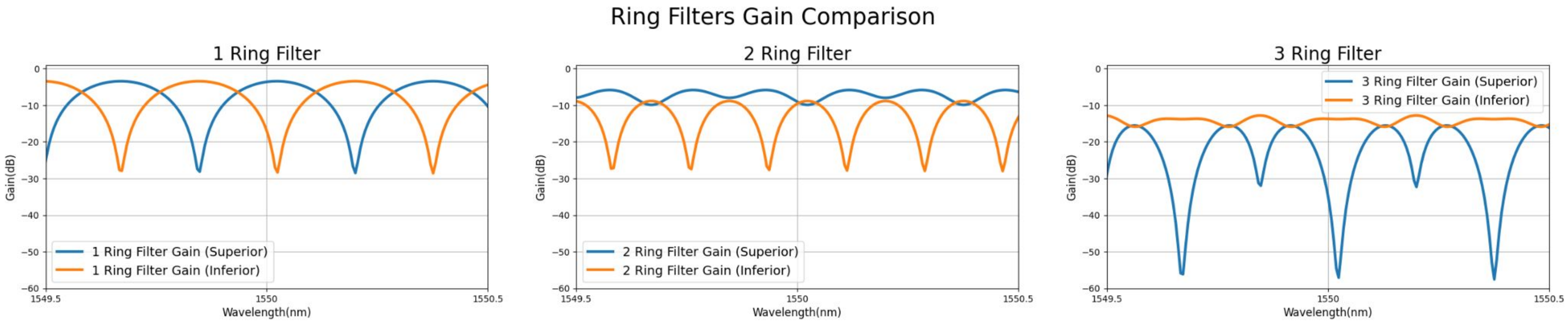
Theta A are external arm phases and Theta B internal arm phases.

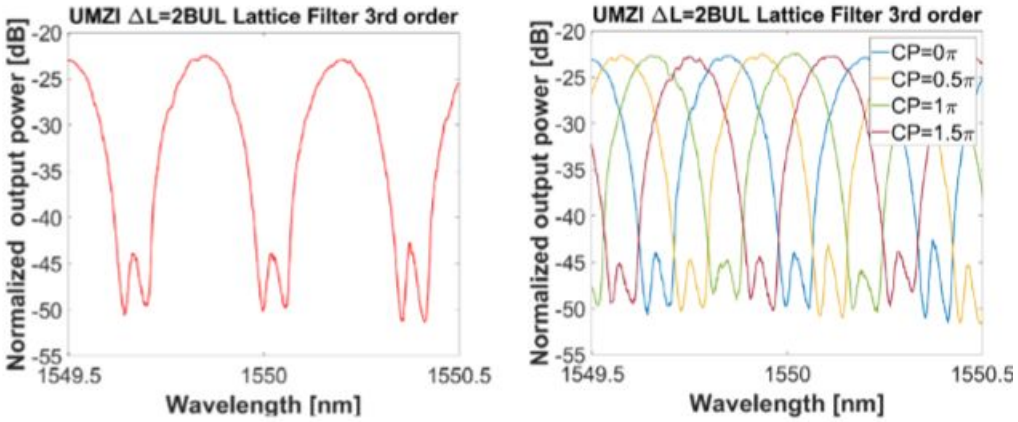


MZI Hex generation

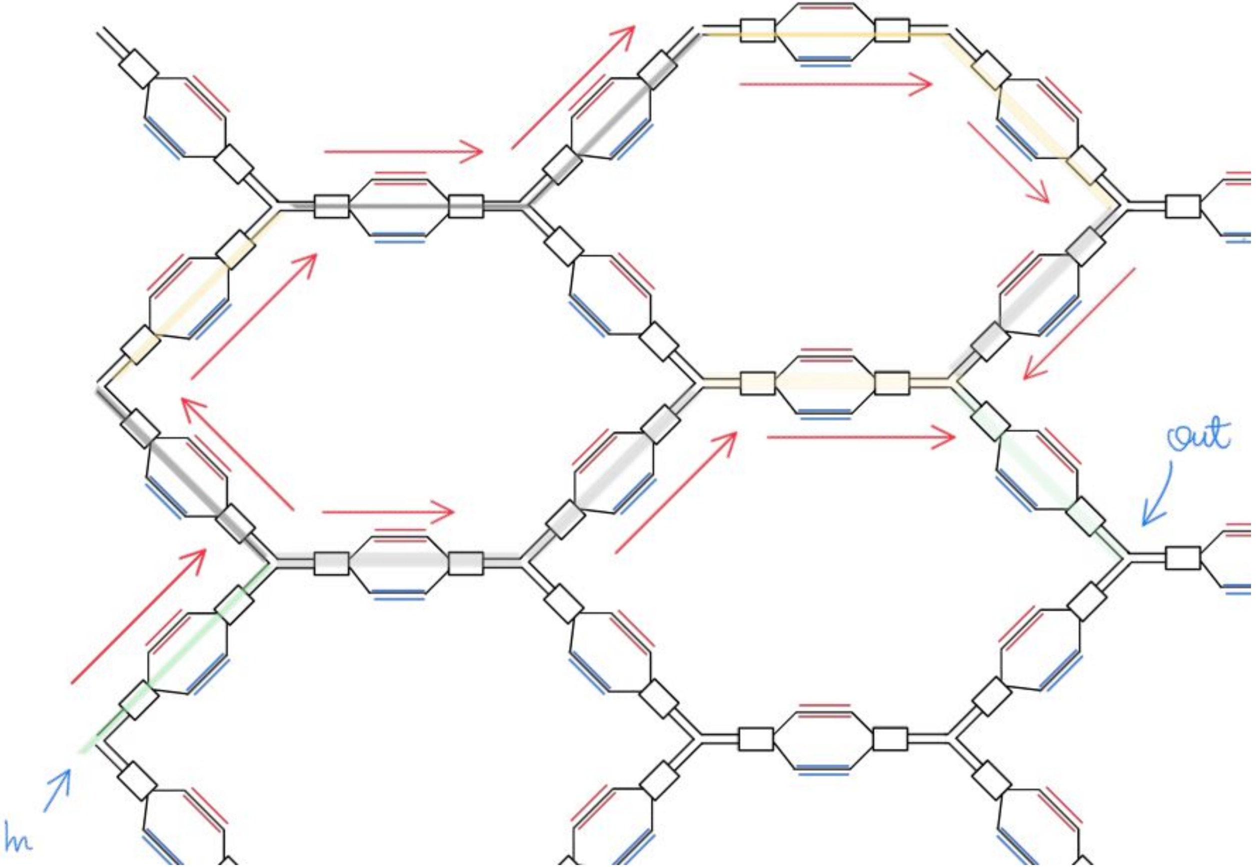
```python
def GenerateHexMZI(Loss: float, process: str, theta_matrix: list[list[float]]):
    """
    GenerateHexMZI is a function that simulates a hexagonal MZI (Mach-Zehnder Interferometer) setup.

    Parameters:
    - Loss (float): A floating-point number representing the loss on each MZI.
    - process (ModuleType): Lumerical API used.
    - theta_matrix (list[list[float]]): A 2D list (6x2 matrix) where each row contains
      two floating-point numbers representing thetaA and thetaB in radians.

    Returns:
    None
    """

    process.addelement('MZI_HEX')
    process.set('Loss',Loss)

    # Set the phase of the MZIs
    for i, (thetaA, thetaB) in enumerate(theta_matrix):
        process.set('Theta'+str(i+1)+'_A', thetaA)
        process.set('Theta'+str(i+1)+'_B', thetaB)
```

UMZI Results



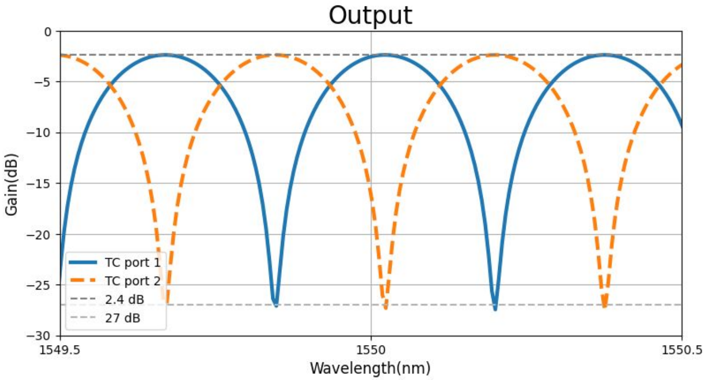


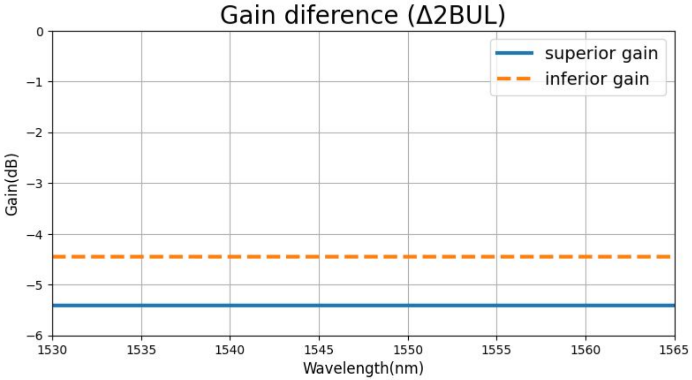
UMZI Unitary Cell with 4Δ BUL



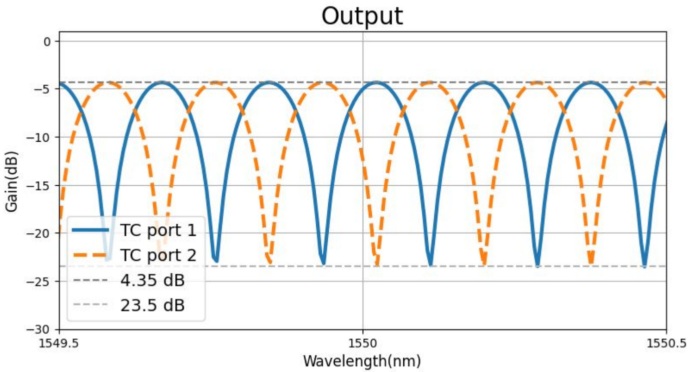
UMZI Unitary Cell difference

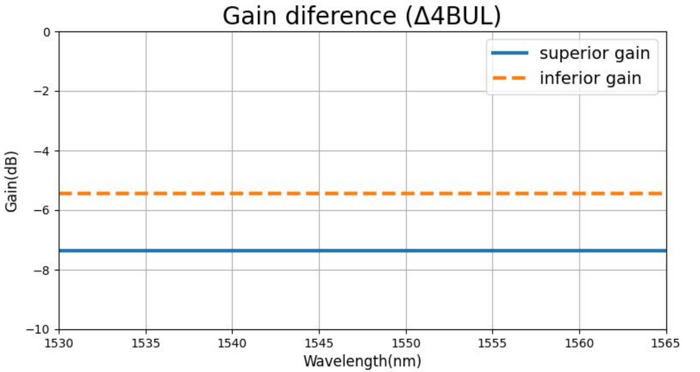
UMZI unitary filter cell (Using 0.48dB loss per BUL)



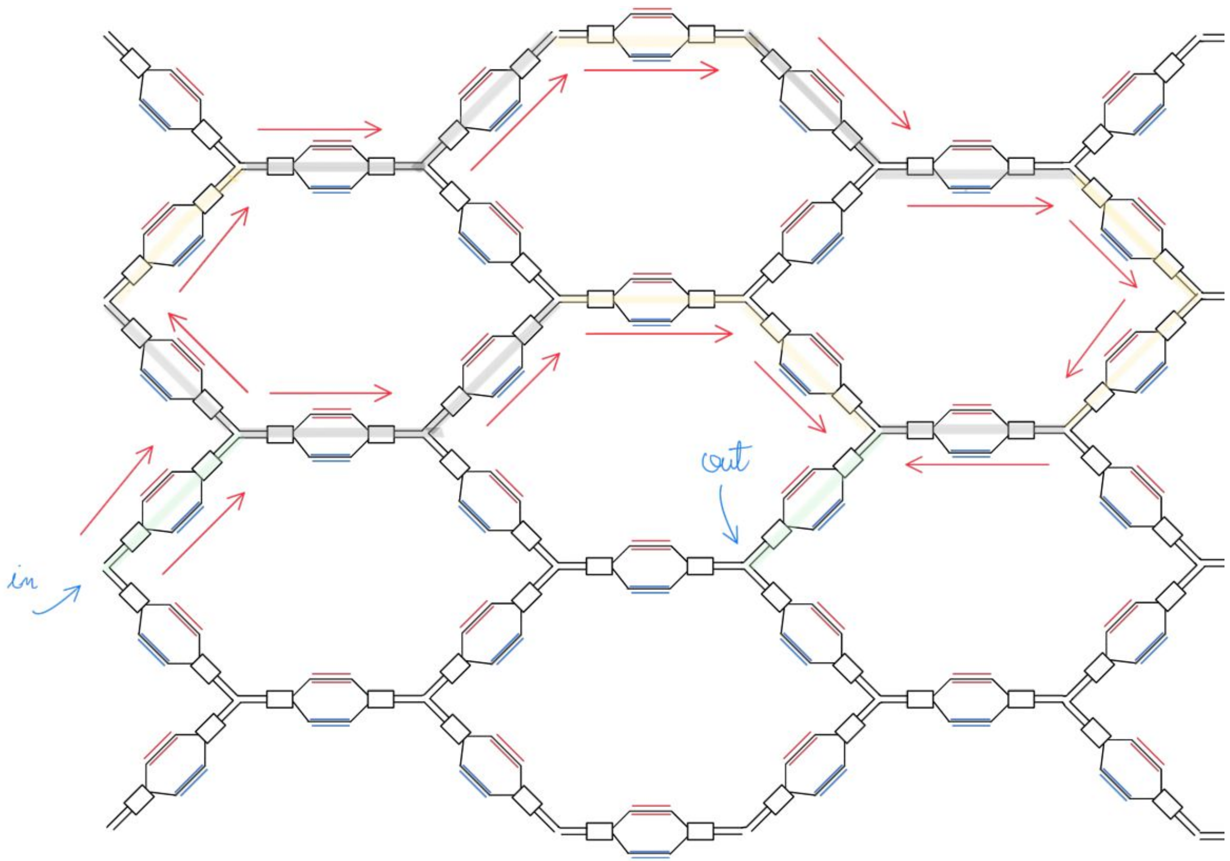


UMZI unitary filter cell With 4BUL difference



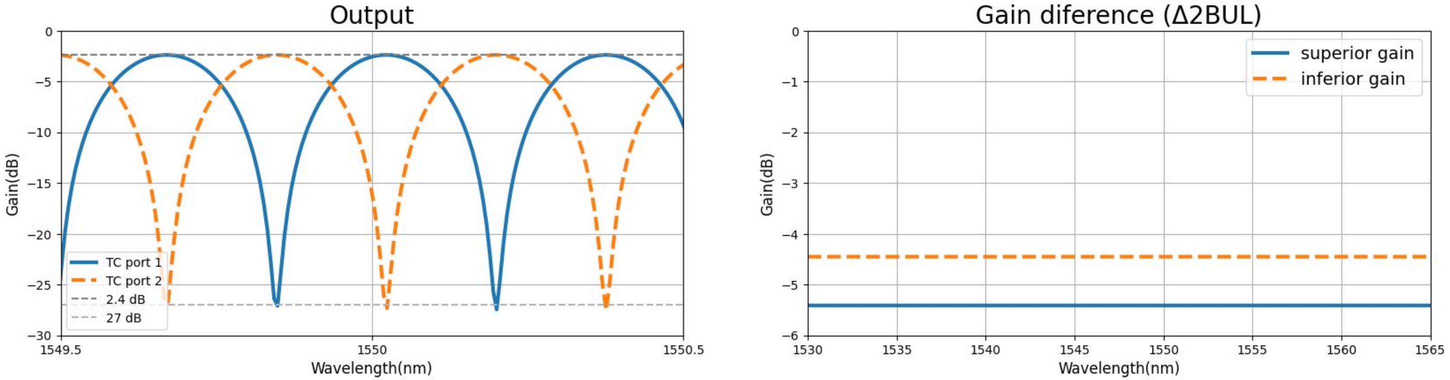


UMZI Unitary Cell with 6Δ BUL

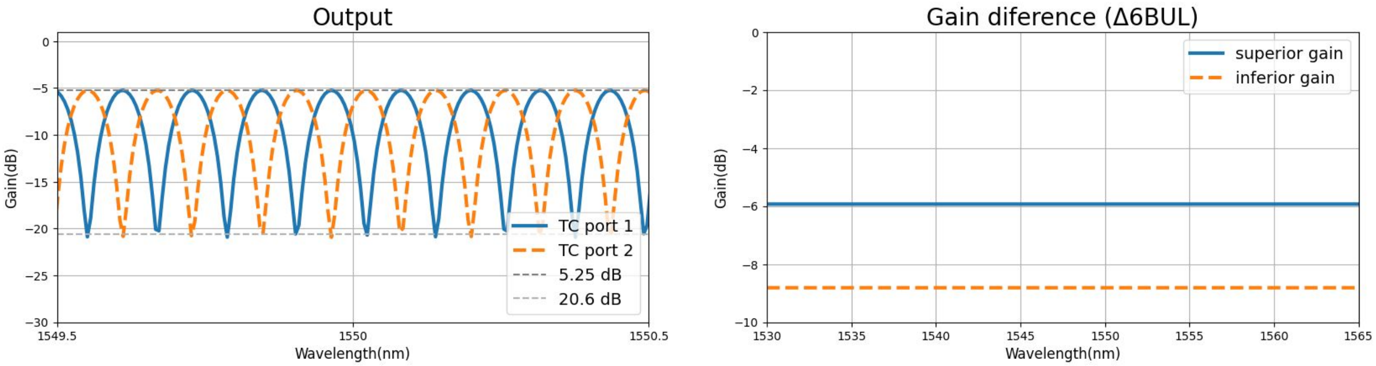


UMZI Unitary Cell difference

UMZI unitary filter cell (Using 0.48dB loss per BUL)



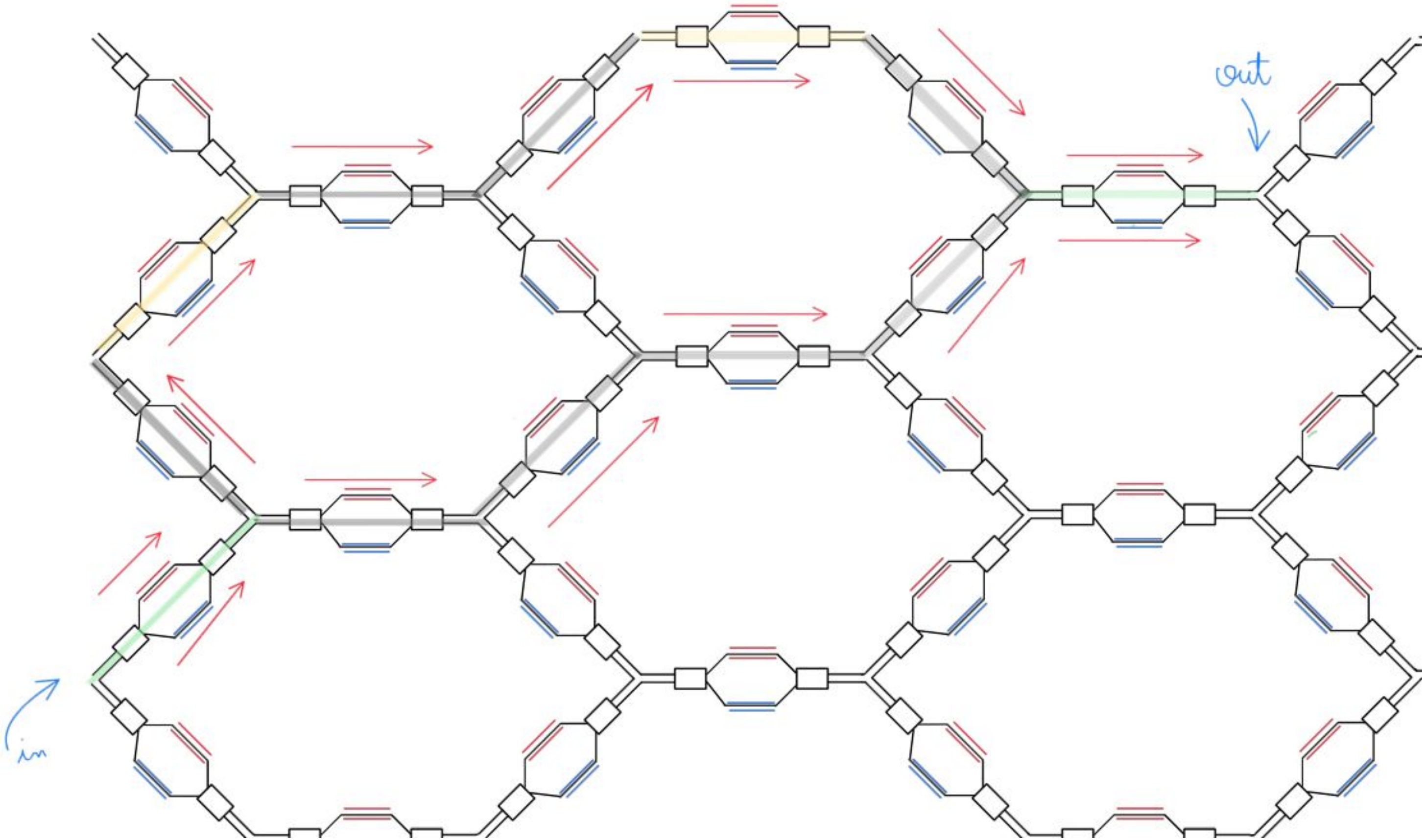
UMZI unitary filter cell With 6BUL difference



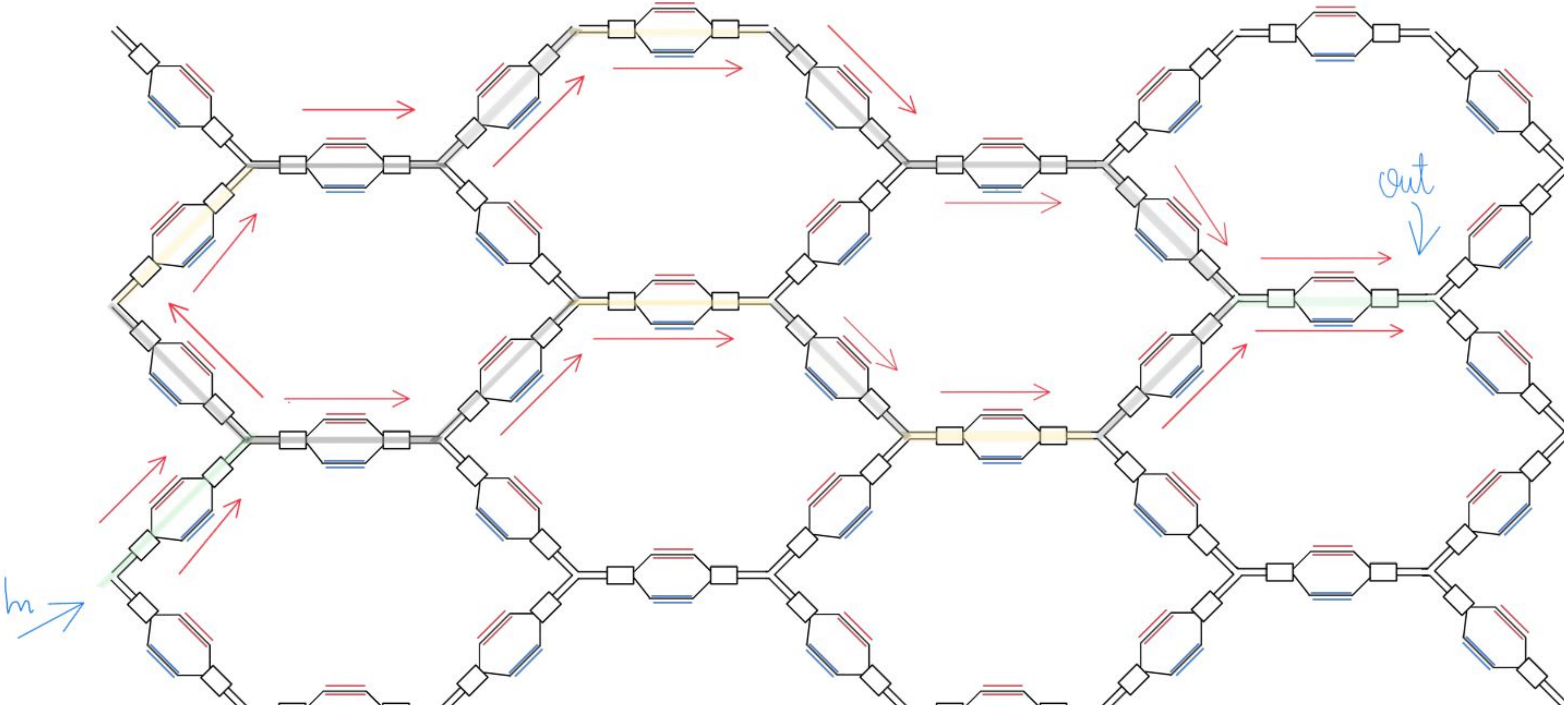
Testing length differences and coupling coefficients

03/09-10/09

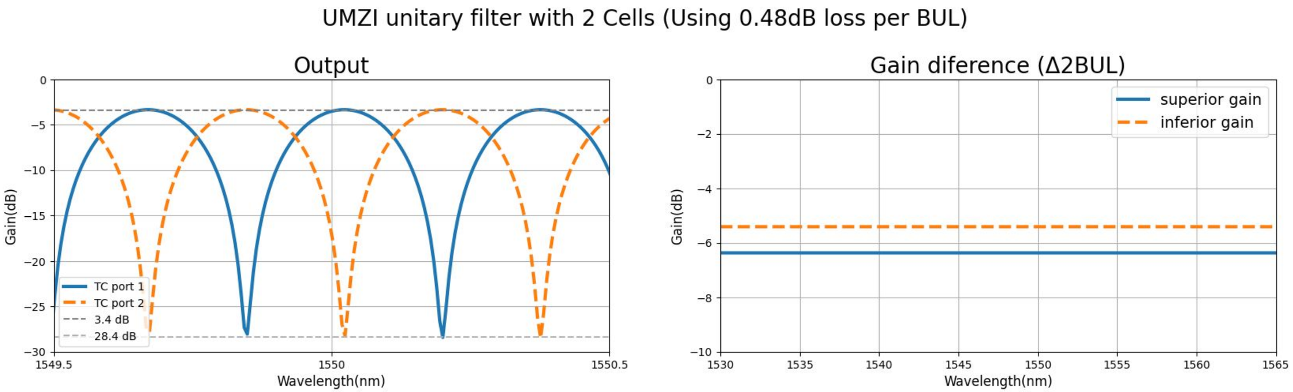
UMZI Unitary Cell with 2 Cells length

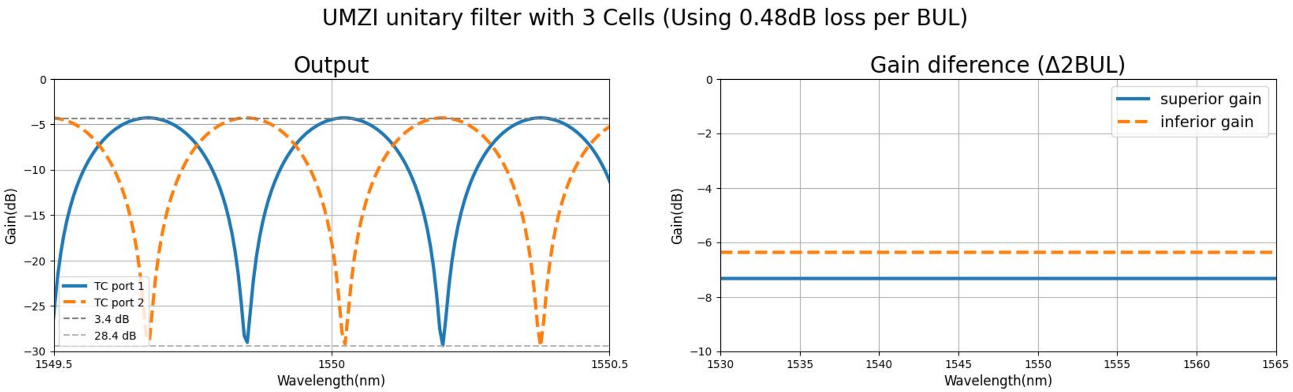


UMZI Unitary Cell with 3 Cells length



UMZI Unitary Cell difference

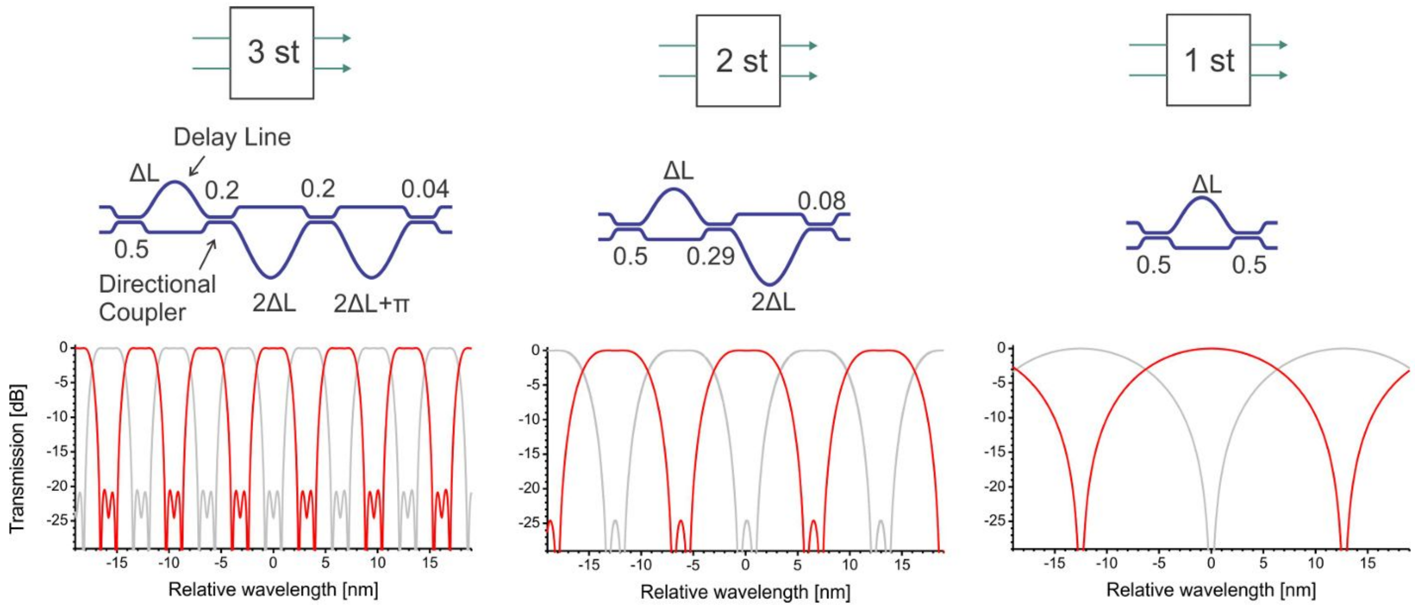




Modeling MZI in function of phase difference

10/09-19/09

Cascaded Mach-Zehnder wavelength filters in silicon photonics for low loss and flat pass-band WDM (de-)multiplexing



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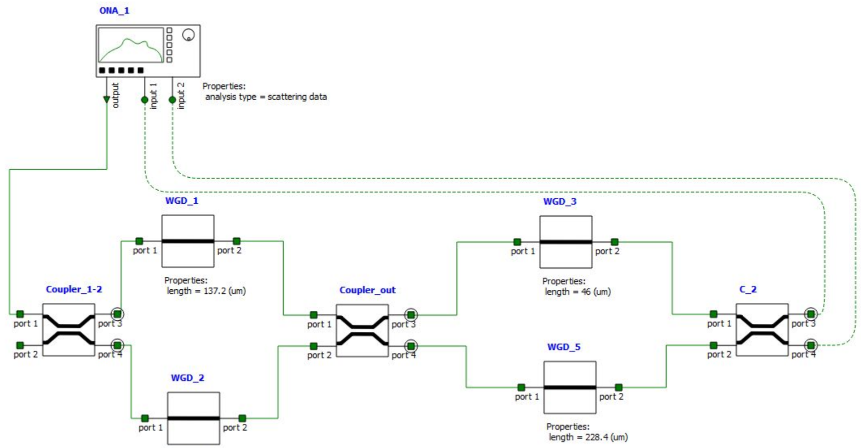
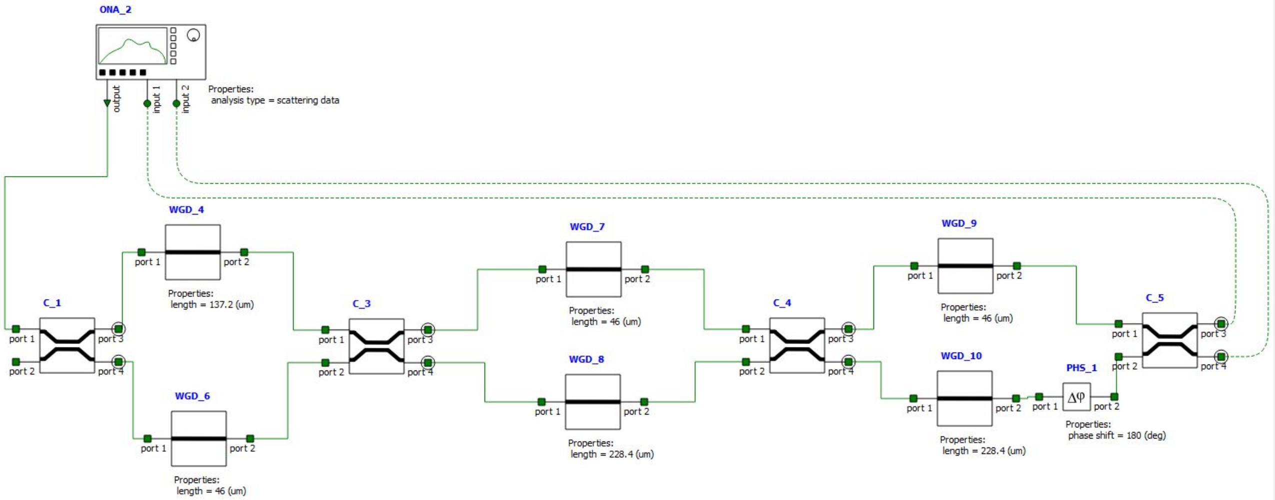
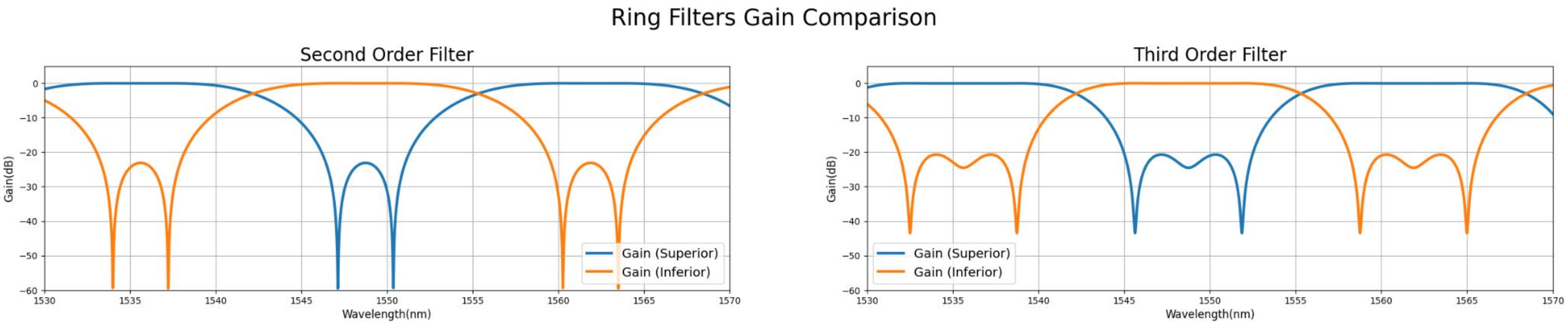
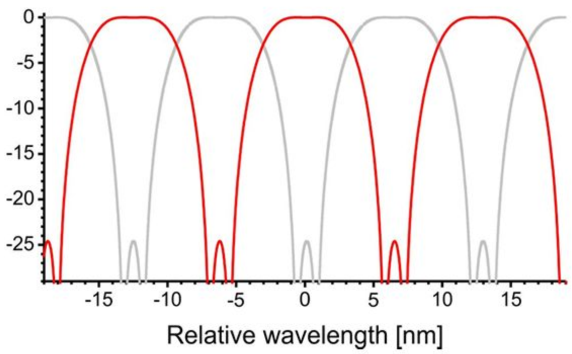
Replicating 2 st and 3 st using couplers

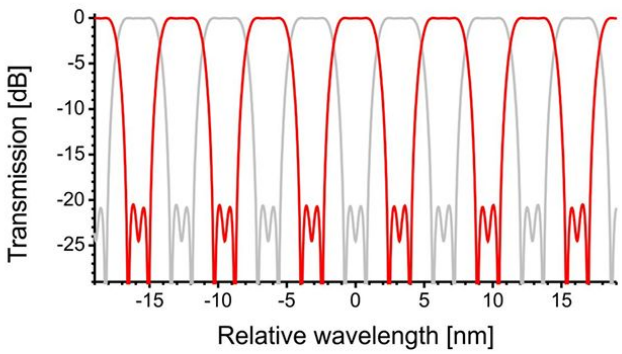




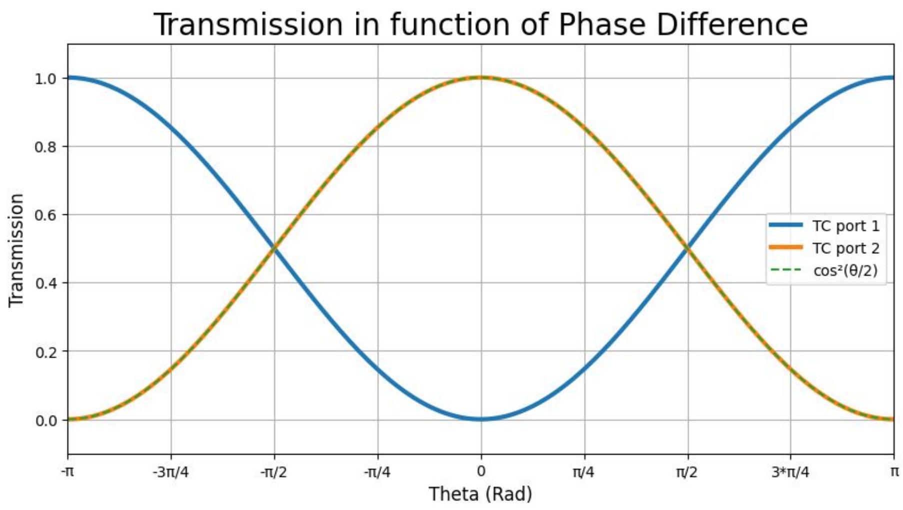
Replicating 2 st and 3 st using couplers

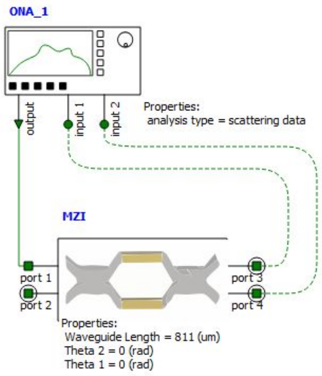






MZI as an optical coupler



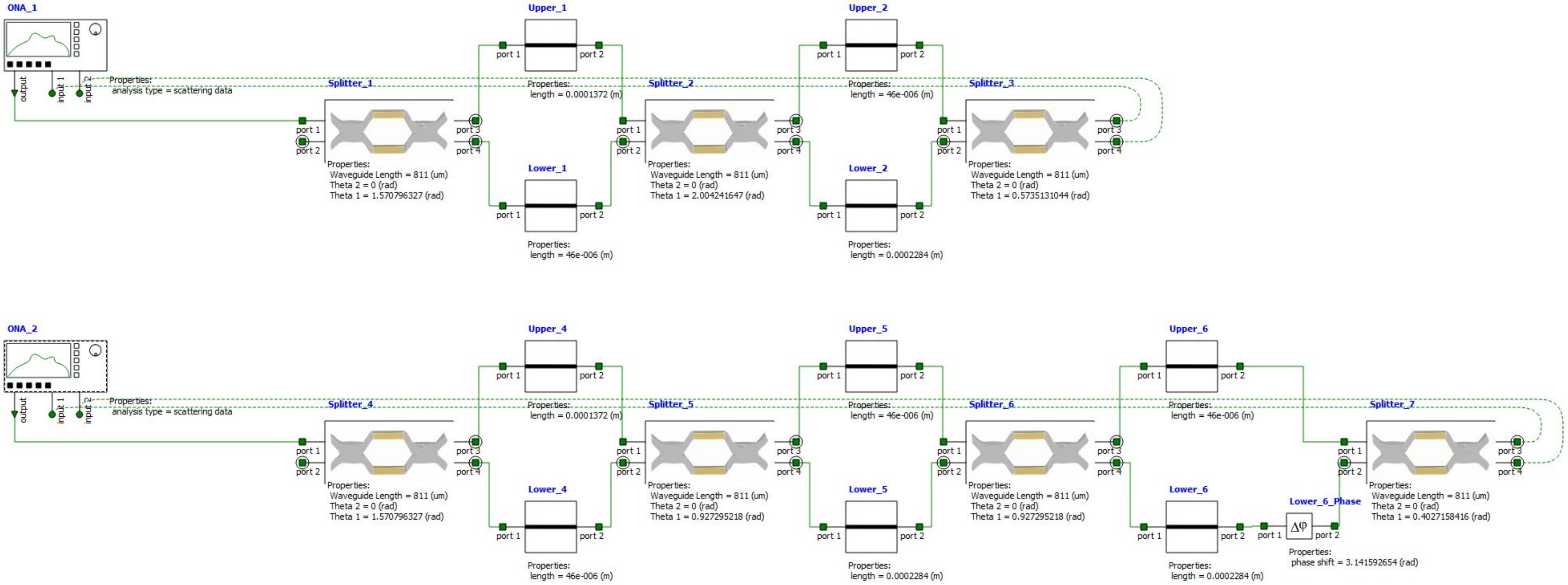



```python
# with the graph above, we can model the MZI
# as an coupler with cos²(θ/2)

theta1 = 2*np.arccos(np.sqrt(0.5))
theta2 = 2*np.arccos(np.sqrt(0.29))
theta3 = 2*np.arccos(np.sqrt(0.92))
theta4 = 2*np.arccos(np.sqrt(0.8))
theta5 = 2*np.arccos(np.sqrt(0.96))


print('splitter 0.50 ->',theta1,'(rad)')
print('splitter 0.29 ->',theta2,'(rad)')
print('splitter 0.92 ->',theta3,'(rad)')
print('splitter 0.80 ->',theta4,'(rad)')
print('splitter 0.96 ->',theta5,'(rad)')
```

[44] ✓ 0.0s

```
splitter 0.50 -> 1.5707963267948966 (rad)
splitter 0.29 -> 2.0042416468647826 (rad)
splitter 0.92 -> 0.5735131044230966 (rad)
splitter 0.8 -> 0.9272952180016123 (rad)
splitter 0.96 -> 0.402715841580662 (rad)
```

MZI as an optical coupler



MZI as an optical coupler