Nano-Optic Broadband Power Splitter Design via Cycle-Consistent Adversarial Deep Learning

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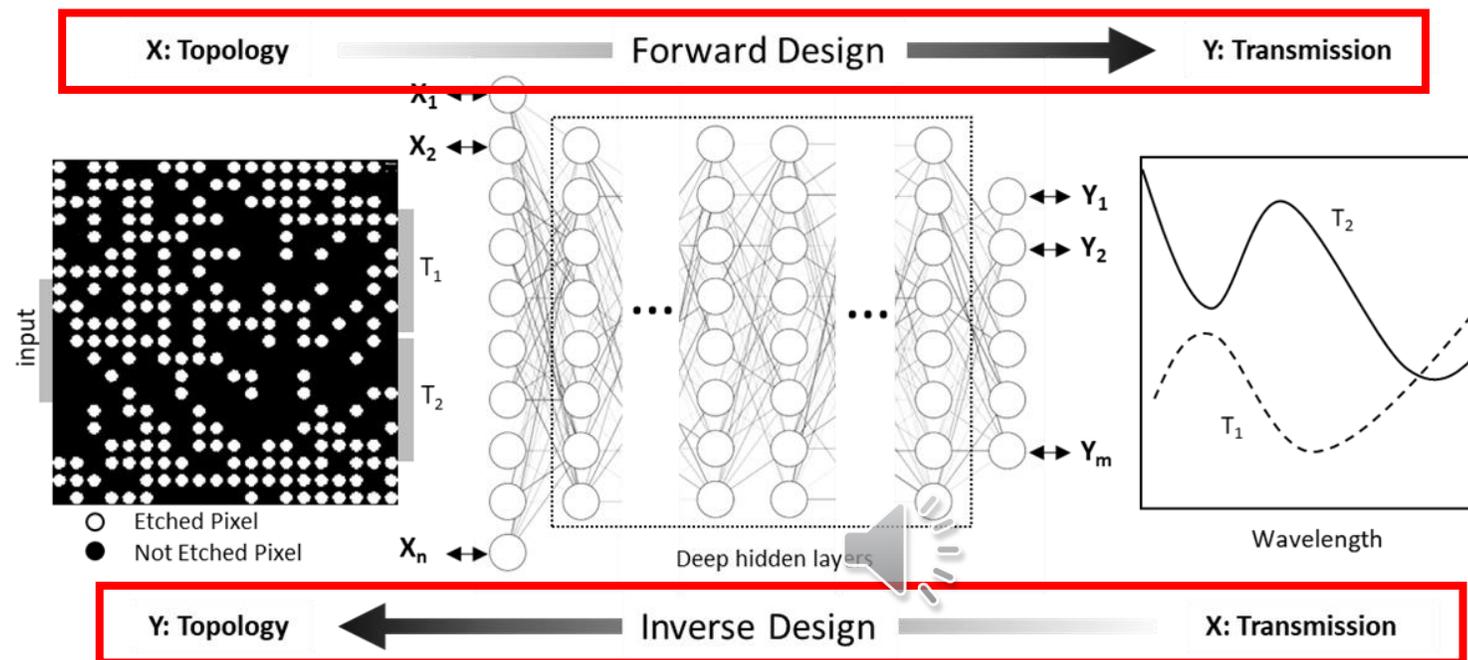
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Outline

- Introduction

- ACVAE model (previous work)

- ACVAE model with cycle-consistency

- Result

- Summary

Introduction

- We want to use the neural network to accelerate the design process for the photonic devices.
- Previously we have created the forward and inverse network.
- The inverse network still has room for further improvement.
- Alternatively, generative modeling, such as conditional variational autoencoders (CVAE) or a generative adversarial network (GAN) can generate improved designs.

Tahersima, M.H., Kojima, K., Koike-Akino, T., Jha, D., Wang, B., Lin, C. and Parsons, K., Scientific Reports (Nature), 2019.
Tahersima, M.H., Kojima, K., Koike-Akino, T., Jha, D., Wang, B., Lin, C. and Parsons, K., OFC, 2019.
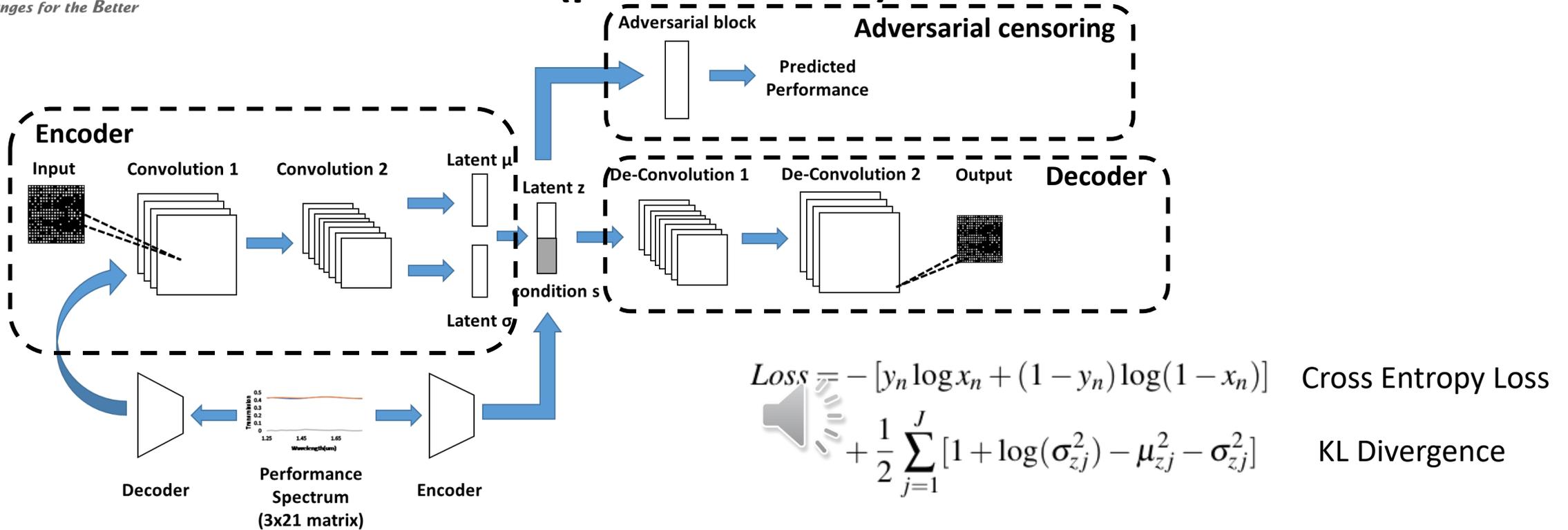
Target Devices: Power splitters

- Arbitrary splitting ratio
- Low Excess loss and low reflection
- Very compact device footprint
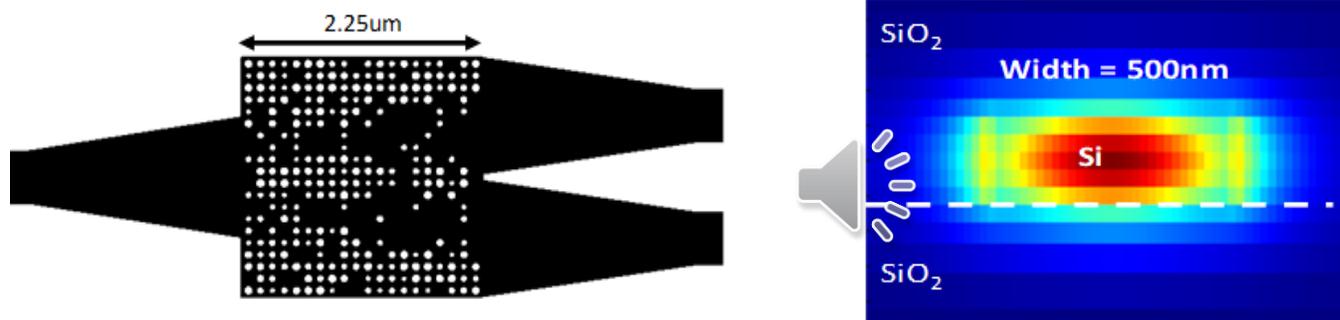
220 nm-thick SOI with SiO2 cladding

40-72 nm-diameter holes etched into Si and filled with SiO_2

113 nm pitch: subwavelength region

Lumerical FDTD: 3D FDTD simulations

The ACVAE model (previous work)

Adversarial block

Adversarial censoring

Predicted Performance

Encoder

Input | Convolution 1 | Convolution 2 | Latent μ

Latent z

De-Convolution 1 | De-Convolution 2 | Output | **Decoder**

condition s

Latent σ

Decoder

Performance Spectrum (3x21 matrix)

Encoder

$$Loss = -[y_n \log x_n + (1 - y_n) \log(1 - x_n)]$$ Cross Entropy Loss

$$+ \frac{1}{2} \sum_{j=1}^{J} [1 + \log(\sigma_{zj}^2) - \mu_{zj}^2 - \sigma_{zj}^2]$$ KL Divergence

- Previously , we used the Adversarial Conditional Variational Autoencoder (A-CVAE) structure to create a generative network for the power splitters with different splitting ratio.
- The adversarial block reduces the leakage of condition information to the latent variables.
- The model can be used to generate the splitters with arbitrary splitting ratio without further optimization process
- We want to further improve the generated device performance (total transmission and splitting ratio) with limited data(especially for the 8:2 device).

Tang, Y., Kojima, K., Koike-Akino, Wang, Y., Wu, P., Xie, Y., Tahersima, M.H., T., Jha, D., Parsons, K., Qi, M., Laser & Photonics Reviews, 2020.
Tang, Y., Kojima, K., Koike-Akino, Wang, Y., Wu, P., Tahersima, M.H., T., Jha, D., Parsons, K., Qi, M., OFC, 2020.

The ACVAE model with cycle consistency

- In addition to the encoder-decoder structure for forward construction, the reversed-order decoder-encoder pipeline is also trained for latent space consistency.
- We hope to apply the cycle-consistency idea to further reduce leakage of information associated with specified factors of latent variation.
- ~16000 training data (including both binary(~15000) and variable hole size (~1000) HV
- Update frequency between CAVE blocks and adversarial blocks is (3:1)
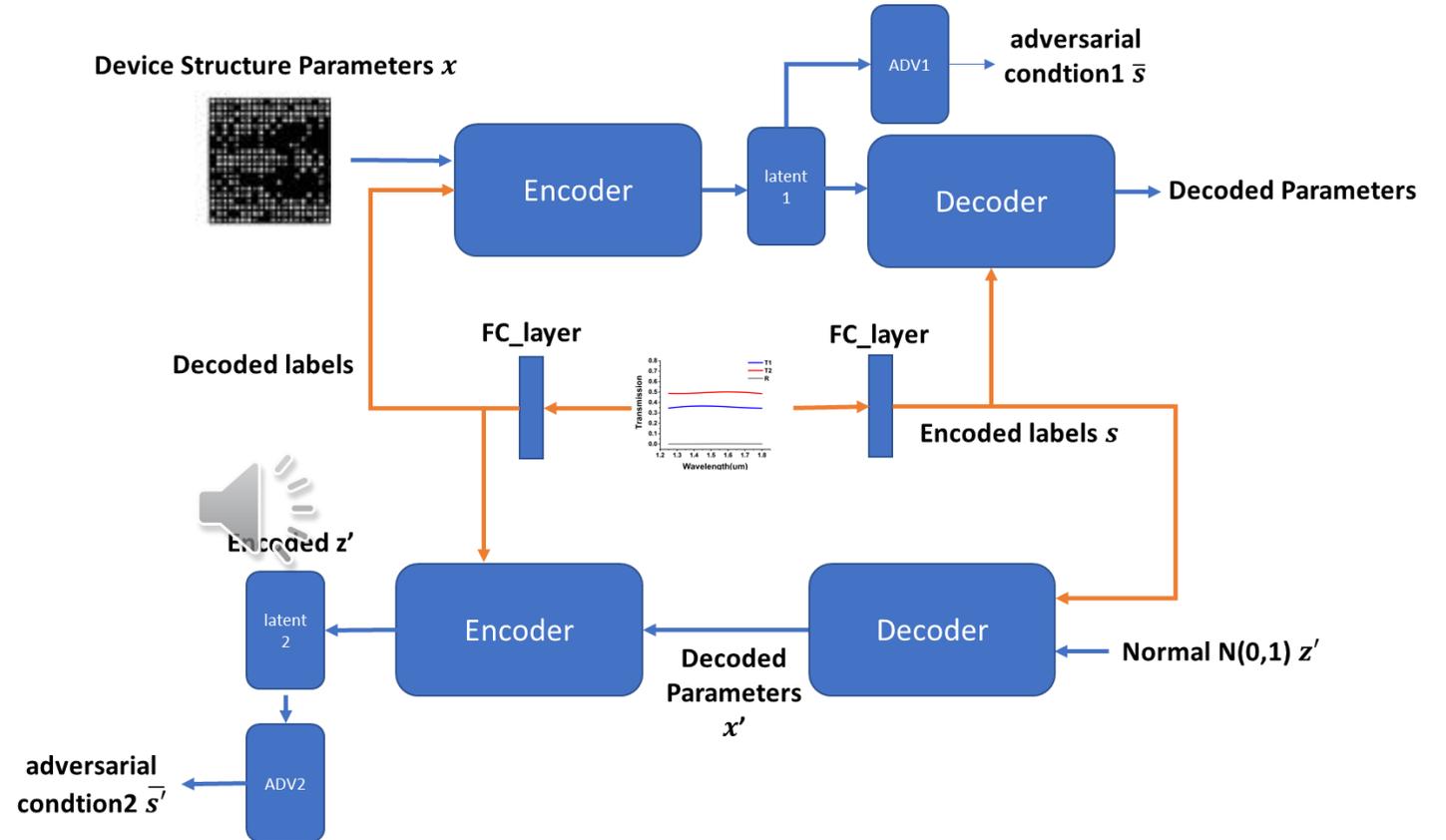
$$Loss = a \cdot \sum_{i=1}^{n}(x_i, \bar{x}_i)^2 + b \cdot \frac{1}{2}\sum_{j=1}^{J}[1 + \log(\sigma_{zj}^2)^2 - \mu_{zj}^2 - \sigma_{zj}^2]$$

$$+ \alpha \cdot \sum_{i=1}^{n}(s_i, \bar{s}_i)^2 + \gamma \cdot \sum_{i=1}^{n}(z_i, \bar{z}_i)^2 + \beta \cdot \sum_{i=1}^{n}(s'_i, \overline{s'}_i)^2$$
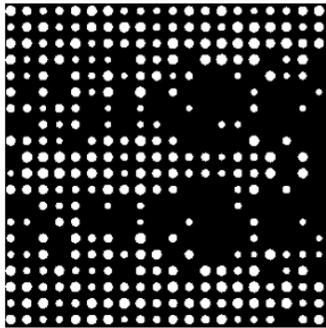
The ACVAE model with cycle consistency

- Detail network parameters for the Encoders and Decodes

Layer	Encoder	Decoder
1	Convolution (channel= 16, kernel = 3, stride = 1, padding =1)	MLP((60 + 9) -> 800
2	Batchnorm(16)	Convolution (channel= 32, kernel = 3, stride = 2, padding =1)
3	Relu + Maxpooling	Batchnorm(32)
4	Convolution (channel= 32, kernel = 3, stride = 1, padding =1)	Convolution (channel= 16, kernel = 3, stride = 2, padding =1)
5	Batchnorm(32)	Batchnorm(16)
6	Relu + Maxpooling	Sigmoid
7	MLP (800 -> 60) + Relu	

Result (power splitter)

- Four different types of devices are generated with the splitting ratio of 5:5, 6:4, 7:3, 8:2
- The overall total transmission is ~ 90% across the large bandwidth (550nm), the actual splitting ratio is very close to the target.
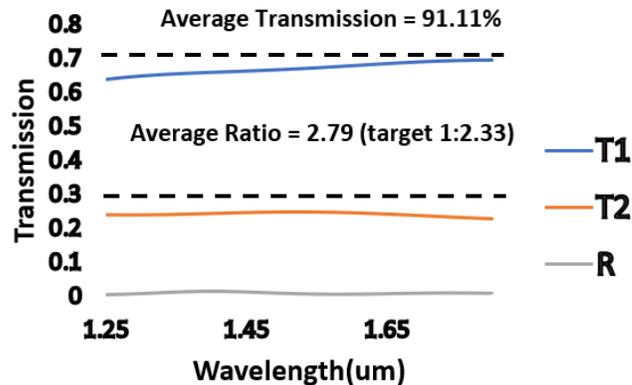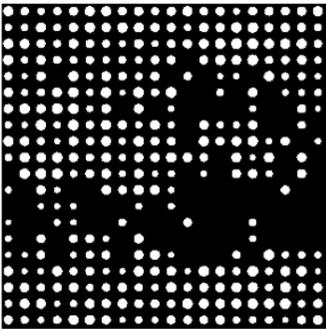

a.5:5

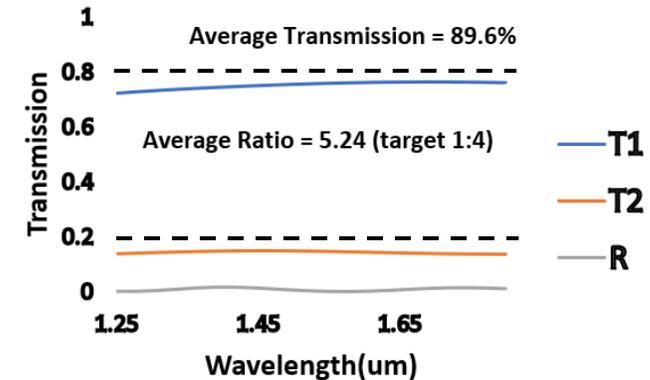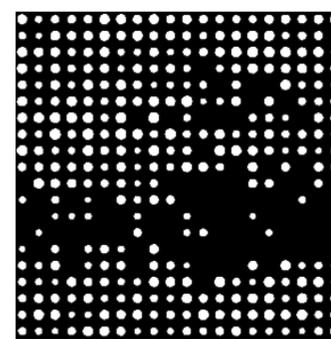Average Transmission = 89%

Average Ratio = 1.009 (target 1:1)

b.6:4

Average Transmission = 90.4%

Average Ratio = 1.56 (target 1:1.5)

c.7:3

Average Transmission = 91.11%

Average Ratio = 2.79 (target 1:2.33)

d.8:2

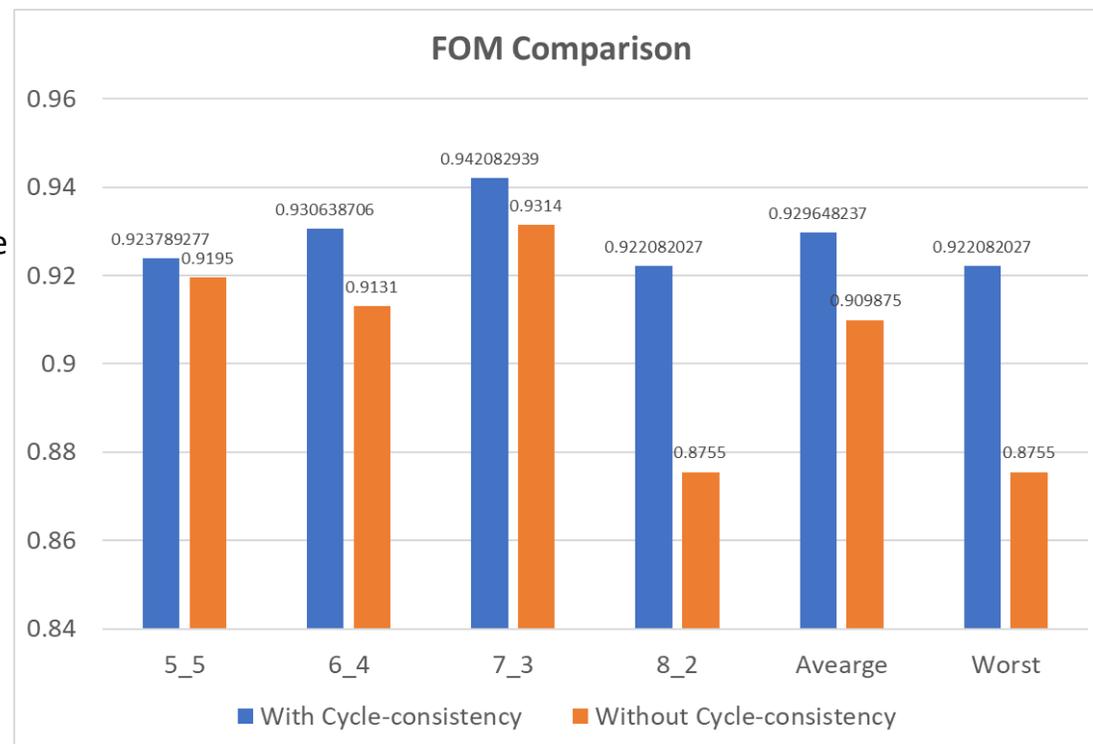Average Transmission = 89.6%

Average Ratio = 5.24 (target 1:4)
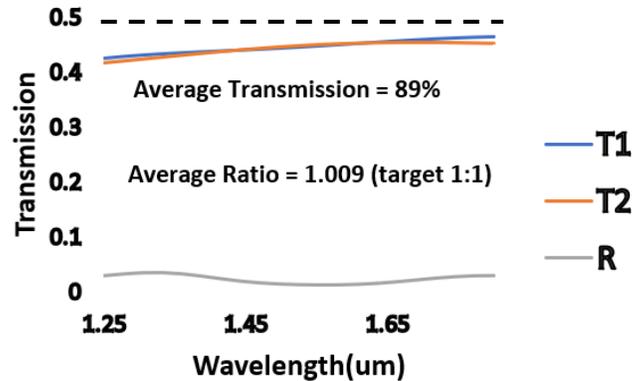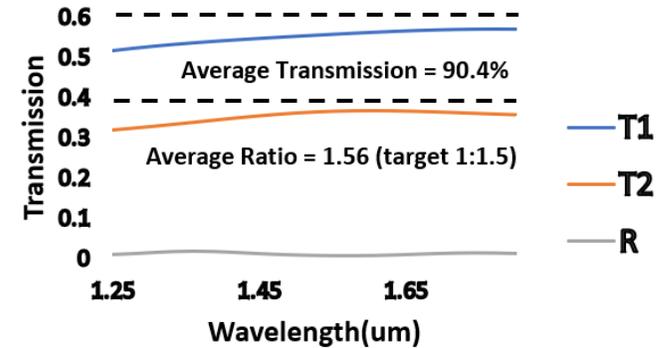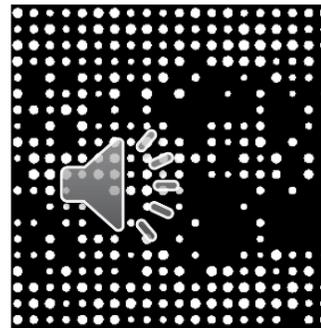
Result (power splitter)

- We introduce the Figure of Merit(FOM) to better describe the device optical performance
- The FOM comparison between the Adversarial CVAE with/without the cycle-consistency
- Generate 50 devices for each type of splitter(5_5, 6_4, 7_3 and 8_2)
- Running FDTD simulation and calculate the average FOM for each type of devices and the overall FOM
- The comparison of FOM shows decent improvement using the new model (with cycle consistency)

$$FOM = 1 - 10 * \left[\int_a^b [T_1(\lambda) - T_1^*(\lambda)]^2 d\lambda + \int_a^b [T_2(\lambda) - T_2^*(\lambda)]^2 d\lambda + \alpha \int_a^b R(\lambda)^2 d\lambda \right]$$

Transmission difference of Output Port 1

Transmission difference of Output Port 2

Reflection difference of Input Port

FOM Comparison

	5_5	6_4	7_3	8_2	Avearge	Worst
With Cycle-consistency	0.923789277	0.930638706	0.942082939	0.922082027	0.929648237	0.922082027
Without Cycle-consistency	0.9195	0.9131	0.9314	0.8755	0.909875	0.8755

■ With Cycle-consistency   ■ Without Cycle-consistency
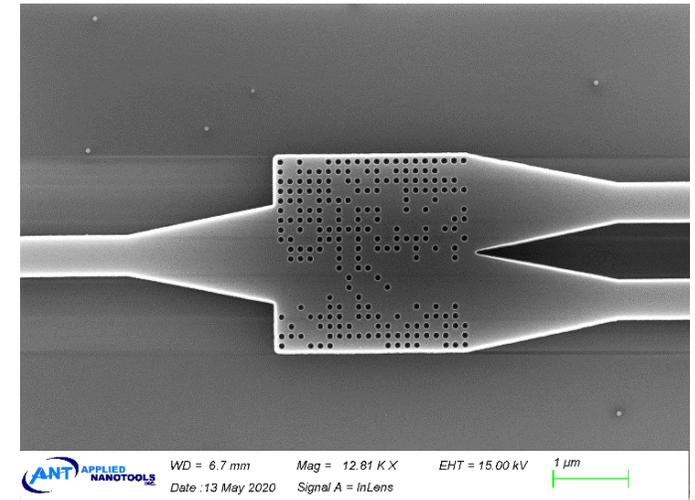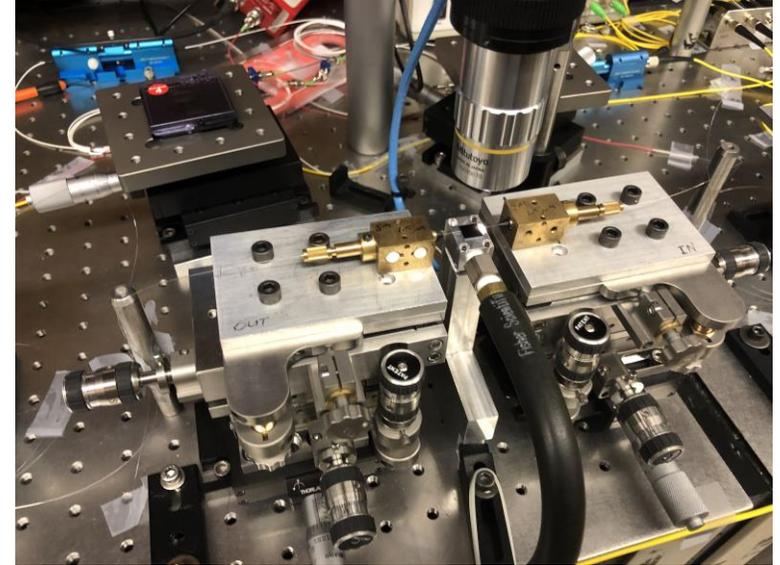
Result (WDM splitter)

- Using the same platform, we generated WDM filters targeting different wavelengths.

- 16 optimization runs are conducted targeting different wavelengths.

- Total of 21,530 the training data.

- We tried ACVAE with and without cycle consistency.

- We picked the WDM splitter with the longest wavelength and tried to generate new devices with +40nm and +80nm shifted targets (extrapolation).

- ACVAE-CC gives better splitter performances
  - Less change in the transmittance peak/bottom

Training data example

ACVAE

ACVAE-CC
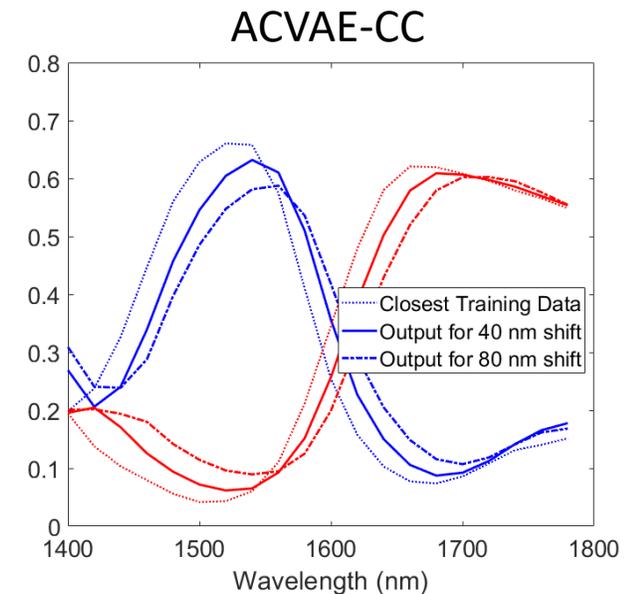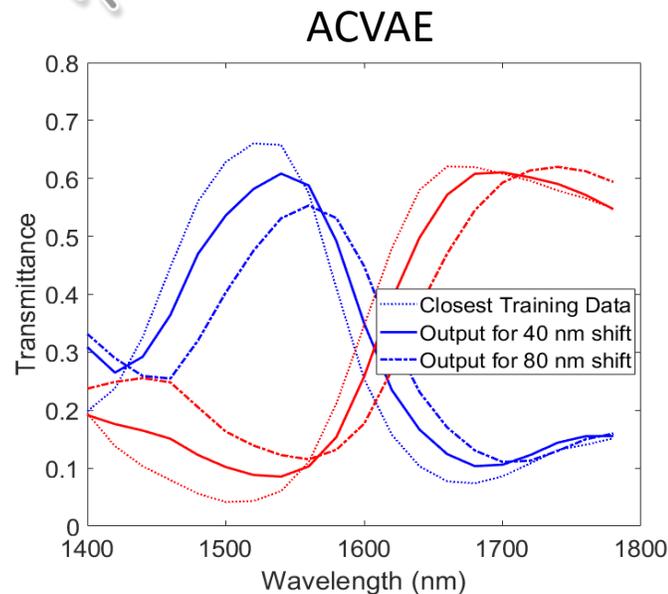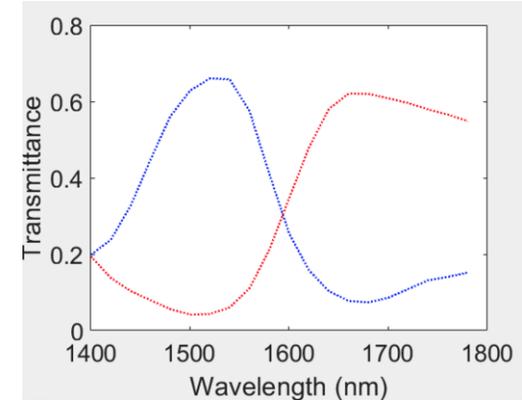
Result (beam splitter measurement result)

- The chip and the mask is designed at MERL and is fabricated through external foundry(Applied Nanotools).
- Edge coupling measurement of the power splitter is conducted in Purdue (total transmission and power splitting ratio).
- For the first version of the devices, we put devices with constant hole size as well to increase the chance of success
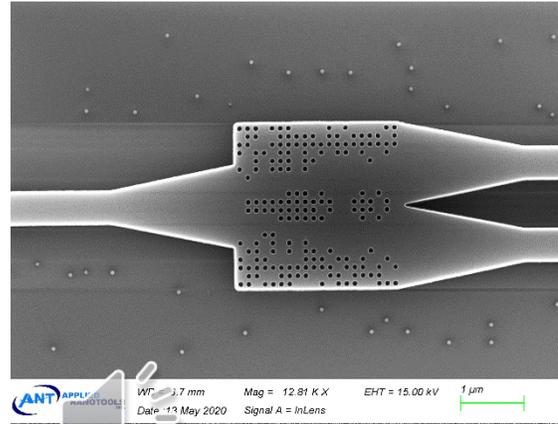
```
┌──────────┐  Edge coupling  ┌──────────┐  Edge coupling  ┌──────────┐
│  Source  │ ──────────────► │   DUT    │ ──────────────► │  Power   │
│          │                 │          │                 │  meter   │
└──────────┘                 └──────────┘                 └──────────┘
```
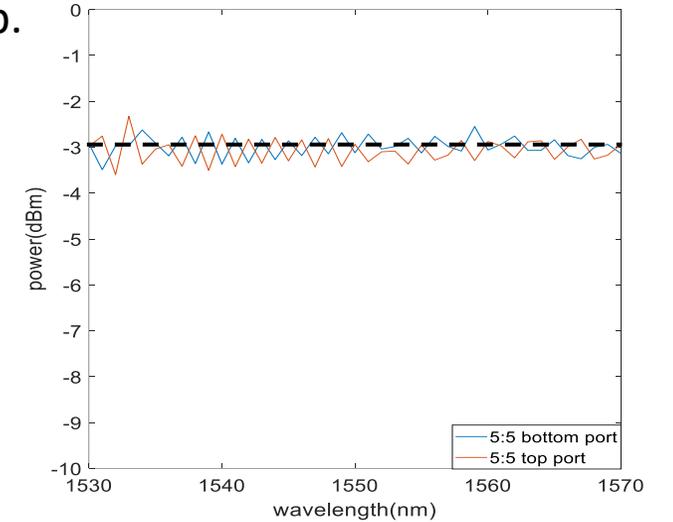
Result (beam splitter measurement result)

- Overall, 5:5 and 6:4 device have shown good performance with small loss.
- For 5:5 device, the splitting ratio is close to 1 and the insertion loss is ~-0.5dB
- For 6:4 device, the splitting ratio is ranging from 0.708 to 0.631 (target:0.67) and the insertion loss is ~-0.3dB
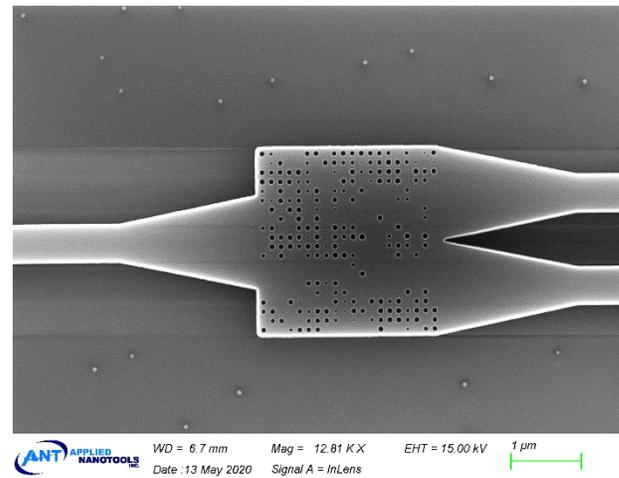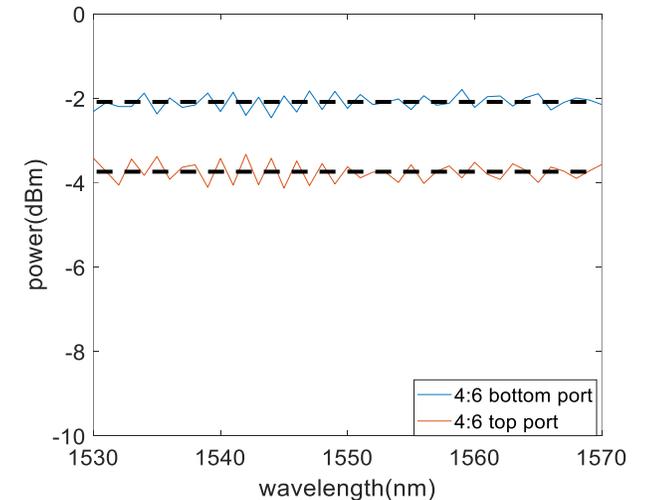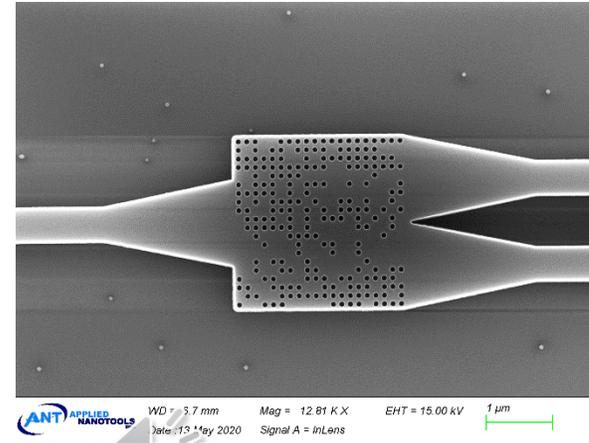
Device (5:5)

a.

b.

Device (6:4)

a.

b.

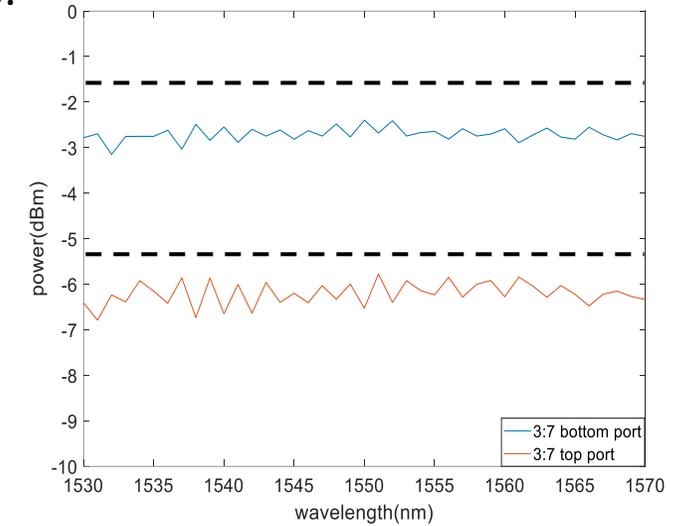# Result (beam splitter measurement result)

- The insertion loss for the 7:3 and 8:2 devices are larger.
- For 7:3 device, the splitting ratio is ranging from 0.51 to 0.38 (target:0.43) with insertion loss to be -2.5dB
- For 8:2 device, the splitting ratio is ranging from 0.32 to 0.26 (target :0.25) with insertion loss to be -1dB
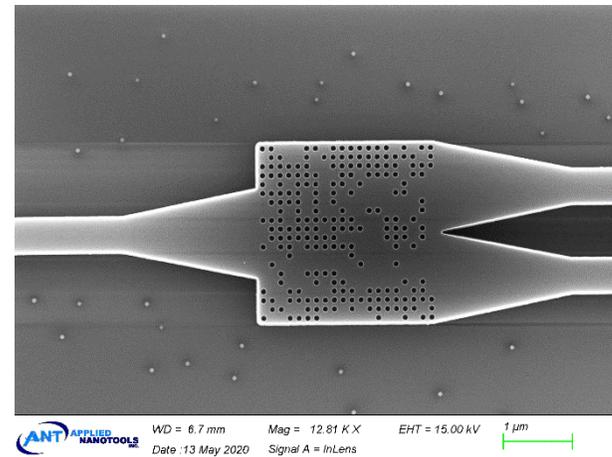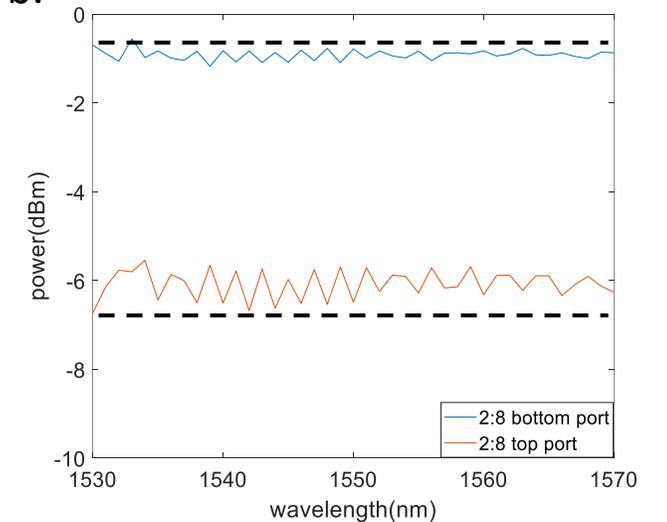
Device (7:3)

a.

b.

Device (8:2)

a.

b.

Summary

- We further improved the ACVAE model by applying the cycle consistency concept to it.
- The model can be used to generate the splitters with arbitrary splitting ratio without further optimization process
- The final generated devices can reach over 90% transmission across a wide bandwidth (1250nm – 1800nm)
- The ACVAE model with cycle consistency also shows decent improvement from our previous ACVAE model in terms of Figure of Merit (FOM).
- Some measurements have been performed to experimentally prove our model-generated devices are functioning properly.

Thank you