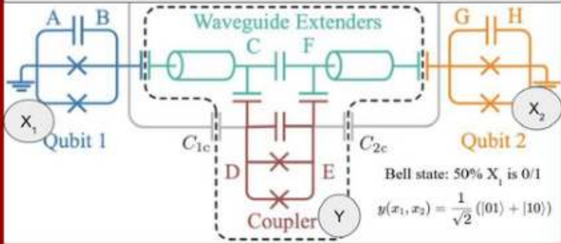
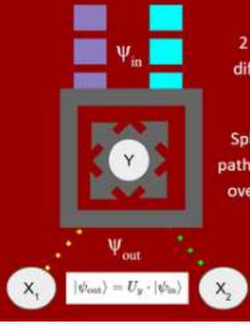
Quantum Circuits

Core concept: Qubits store quantum information, but to actually perform computation, they must interact to carry out logic





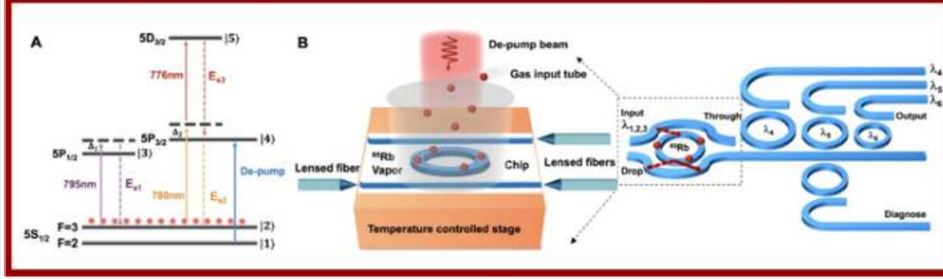
Input:
2 photons on different paths

Coupler:
Splits/mixes the paths, letting states overlap/interact.

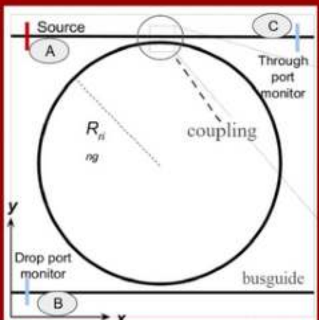
Output:
Two entangled photons

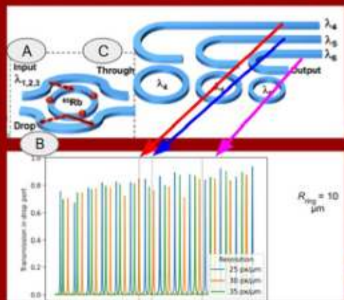
Spontaneous Six Wave Mixing Microring

Microrings are traditionally used in classical photonics to support computation, but this work advances their role towards being an active element in the execution of quantum logic.

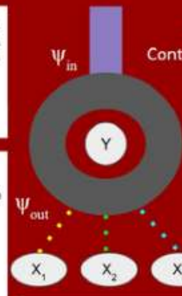


SSWM Microring





Output: 3 entangled photons at specific wavelengths



$|\psi_{out}\rangle = |\alpha\rangle_p \otimes (|000\rangle + |111\rangle)/\sqrt{2}$

Input:
Continuous laser

Coupler:
Spontaneous Four Wave Mixing

Output:
3 qubits

Feature	Traditional	SSWM	Benefit
Input	Pre-existing photons	Classical pump laser	Eliminates the need for separate sources
Photon Generation	No	Yes via SFWM	Reduces system complexity
Main Function	Mixes/redirects existing photons	Generates and entangled photons	Combines two functions
Entanglement	Interference of input photons	Created during generation	—
Tunability	Usually fixed	Tunable via resonance	Dynamic control

Goal: Increased integration density increases computational power, reduces photon loss & latency, and enables complex multi-qubit operations.

Decoupling:

Decoupling is when the microring is tuned so that it does not transfer photons into the circuit.

Refractive Index Thermal Tuning

n = refractive index
κ = coupling
β = propagation

$$\Delta n = |n_{bus} - n_{ring}| \gg 0 \quad \beta = \frac{2\pi n_{eff}}{\lambda_0}$$

$$\Delta\beta = |\beta_{bus} - \beta_{ring}| = \frac{2\pi}{\lambda_0} \cdot \Delta n \gg 0$$

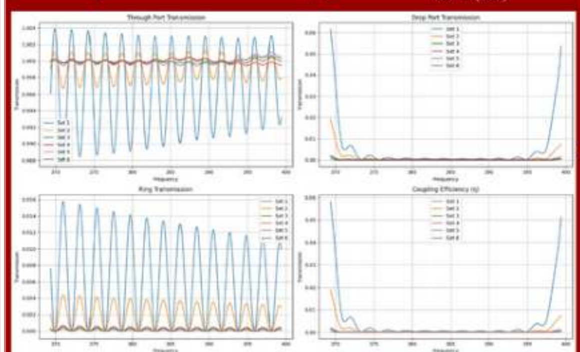
$$\kappa \propto \exp(-\alpha \cdot \Delta n)$$ As Δn ↑; κ ↓, Δβ ↑

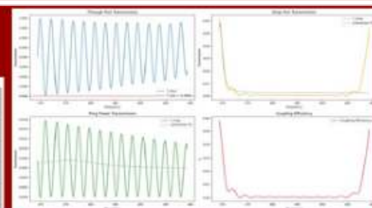
Name	Control	Exp	Exp 2	Exp 3	Exp 5	Exp 6
n_{bus}	2.05	2.05	2.05	2.05	2.05	2.05
n_{ring}	2.05	2.10	2.15	2.20	2.16	2.17
Δn	0	0.05	0.10	0.15	0.11	0.12

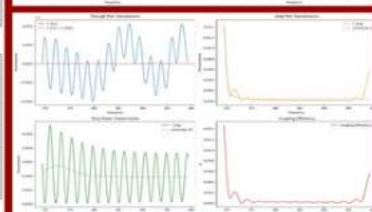
	Set	Extinction Ratio (dB)	Insertion Loss (dB)	Q_drop	Q_drop_fit	Q_ring	Q_ring_fit	T_min	g_coupling
0	Set 1 Control	0.07	12.10	12.33	-335.90	12.86	25.83	0.9880	0.1094
1	Set 2	0.02	17.19	615.46	344.20	12.85	30.29	0.9967	0.0573
2	Set 3 Δn ↑	0.00	34.89	12.33	-521.37	12.41	60.73	0.9997	0.0176
3	Set 4	0.00	28.81	769.32	431.29	12.39	61.76	0.9994	0.0235
4	Set 5	0.01	26.98	12.33	435.03	12.39	-63.37	0.9994	0.0244
5	Set 6 Exp 3	0.00	28.34	820.61	433.38	12.39	62.06	0.9996	0.0200

Graphical Analysis

Combined (BL)
Control (TR)
Set 6 (BR)







Photon Simulation


```
Coupling matrix kappa matrix: Cntrl
[[0.         0.10954451 0.01      ]
 [0.10954451 0.         0.01      ]
 [0.01       0.01       0.        ]]

Coupling matrix kappa_matrix: Set 6
 [[0.   0.   0.01]
 [0.   0.   0.01]
 [0.01 0.01 0.  ]]
```

$$\kappa = \begin{bmatrix} 0 & \kappa_{01} & \kappa_{02} \\ \kappa_{01} & 0 & \kappa_{12} \\ \kappa_{02} & \kappa_{12} & 0 \end{bmatrix}$$

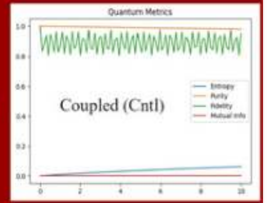
$$\hat{H}_{\text{int}} = \sum_{i<j} \kappa_{ij} (\hat{a}_i^\dagger \hat{a}_j + \hat{a}_j^\dagger \hat{a}_i)$$

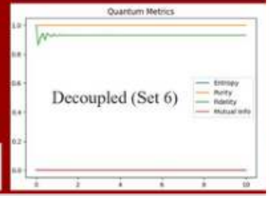
Based on $\hat{H}_{int}$ (κ):

- P_x hop b/w M_x
- P_x decay
- $\langle n_i \rangle = P_x^{Tot}(\Delta t)$

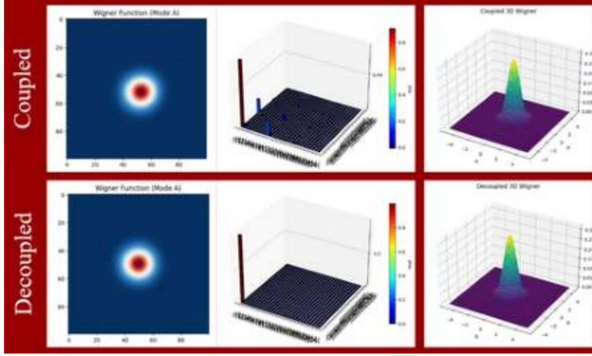
Entropy (↓): mixedness, Purity (↑): clean, Fidelity (↑): close to target.

$$S(\rho) = -\text{Tr}(\rho \log \rho) \quad \text{Purity} = \text{Tr}(\rho^2) \quad F(\rho,\sigma) = \left(\text{Tr}\sqrt{\sqrt{\rho}\sigma\sqrt{\rho}}\right)^2$$

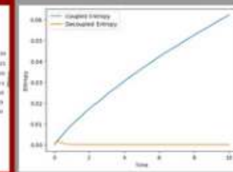




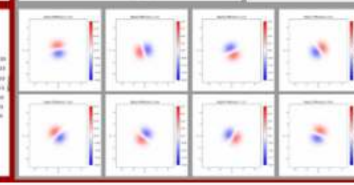
Wigner Plots

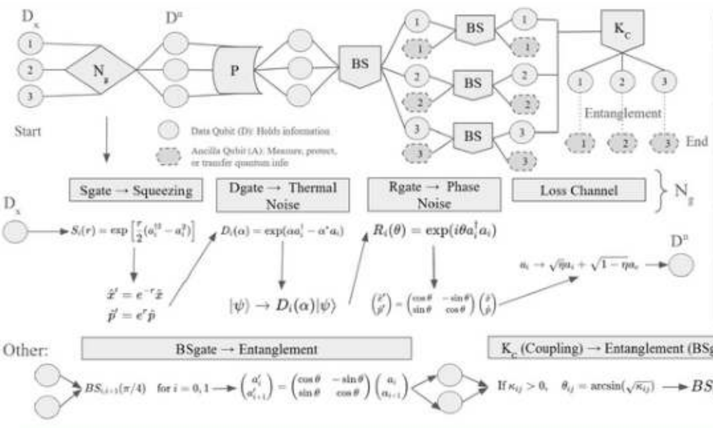


Coupled vs. Decoupled

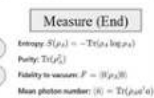


Conclusion: Minimal tuning needed to effectively decouple





Protocol (P)	Gates	Coupling
teleport	Sgate, BSgate, Rgate	Entangle modes 1&2, BS + rotation on 0&1
simple_squeezing	Sgate, BSgate	Squeeze all, BS couple neighbors
displace_entangle	Dgate, Sgate, BSgate	Displacement + entangle 0&1, BS 1&2
phase_rotation_chain	Rgate, BSgate	Rotate all, BS couple neighbors
multi_squeezed_bscoupler	Sgate, BSgate	Squeeze all, BS couple data-ancilla

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ocol to run (options: teleportation, simple_squeezing, displacement_entangle, phase_rotation_chain, multi_squeezed_bscoupler): telep

otocol: teleportation ---

ocol_teleportation | t = 0.00 | (Photon) = 1.989 | Fidelity = 0.279 | Entropy = 29.2139 | Purity = 0.0000 | Gates = 23 | Depth = 22
ocol_teleportation | t = 0.05 | (Photon) = 1.990 | Fidelity = 0.278 | Entropy = 29.1991 | Purity = 0.0000 | Gates = 26 | Depth = 22
ocol_teleportation | t = 0.11 | (Photon) = 1.990 | Fidelity = 0.278 | Entropy = 29.2830 | Purity = 0.0000 | Gates = 26 | Depth = 22
ocol_teleportation | t = 0.16 | (Photon) = 1.992 | Fidelity = 0.276 | Entropy = 29.2771 | Purity = 0.0000 | Gates = 26 | Depth = 22
ocol_teleportation | t = 0.21 | (Photon) = 1.990 | Fidelity = 0.278 | Entropy = 29.2070 | Purity = 0.0000 | Gates = 26 | Depth = 22
ocol_teleportation | t = 0.26 | (Photon) = 1.990 | Fidelity = 0.278 | Entropy = 29.2108 | Purity = 0.0000 | Gates = 26 | Depth = 22
ocol_teleportation | t = 0.32 | (Photon) = 1.989 | Fidelity = 0.279 | Entropy = 29.2245 | Purity = 0.0000 | Gates = 26 | Depth = 22
ocol_teleportation | t = 0.37 | (Photon) = 1.989 | Fidelity = 0.279 | Entropy = 29.2173 | Purity = 0.0000 | Gates = 26 | Depth = 22
ocol_teleportation | t = 0.42 | (Photon) = 1.989 | Fidelity = 0.279 | Entropy = 29.2367 | Purity = 0.0000 | Gates = 26 | Depth = 22
ocol_teleportation | t = 0.47 | (Photon) = 1.990 | Fidelity = 0.278 | Entropy = 29.2130 | Purity = 0.0000 | Gates = 26 | Depth = 22
ocol_teleportation | t = 0.53 | (Photon) = 1.990 | Fidelity = 0.278 | Entropy = 29.2534 | Purity = 0.0000 | Gates = 26 | Depth = 22
ocol_teleportation | t = 0.58 | (Photon) = 1.990 | Fidelity = 0.277 | Entropy = 29.1858 | Purity = 0.0000 | Gates = 26 | Depth = 22
ocol_teleportation | t = 0.63 | (Photon) = 1.990 | Fidelity = 0.278 | Entropy = 29.2105 | Purity = 0.0000 | Gates = 26 | Depth = 22
ocol_teleportation | t = 0.68 | (Photon) = 1.990 | Fidelity = 0.278 | Entropy = 29.4122 | Purity = 0.0000 | Gates = 26 | Depth = 22
ocol_teleportation | t = 0.74 | (Photon) = 1.989 | Fidelity = 0.279 | Entropy = 29.2031 | Purity = 0.0000 | Gates = 26 | Depth = 22
ocol_teleportation | t = 0.79 | (Photon) = 1.990 | Fidelity = 0.278 | Entropy = 29.2125 | Purity = 0.0000 | Gates = 26 | Depth = 22
ocol_teleportation | t = 0.84 | (Photon) = 1.989 | Fidelity = 0.279 | Entropy = 29.2181 | Purity = 0.0000 | Gates = 26 | Depth = 22
ocol_teleportation | t = 0.89 | (Photon) = 1.989 | Fidelity = 0.279 | Entropy = 29.2484 | Purity = 0.0000 | Gates = 26 | Depth = 22
ocol_teleportation | t = 0.95 | (Photon) = 1.992 | Fidelity = 0.276 | Entropy = 29.2492 | Purity = 0.0000 | Gates = 26 | Depth = 22
ocol_teleportation | t = 1.00 | (Photon) = 1.990 | Fidelity = 0.277 | Entropy = 29.2266 | Purity = 0.0000 | Gates = 26 | Depth = 22
PORTATION] [CONTROL]
) | Fidelity: 0.279 | Entropy: 29.1907 | Purity: 0.0000 | Gates: 23 | Depth: 21

PORTATION] [DECOUPLED]
) | Fidelity: 0.278 | Entropy: 29.2791 | Purity: 0.0000 | Gates: 23 | Depth: 22

PORTATION] [COUPLED]
) | Fidelity: 0.278 | Entropy: 29.2137 | Purity: 0.0000 | Gates: 26 | Depth: 22

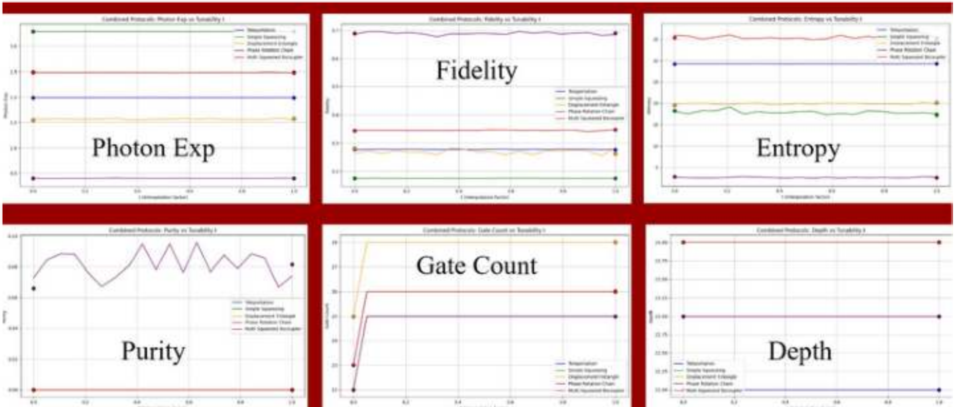
BLE for teleportation ---
on) = 1.989, Fidelity = 0.279, Entropy = 29.1907, Purity = 0.0000, Gates = 23, Depth = 21
oton) = 1.990, Fidelity = 0.278, Entropy = 29.2791, Purity = 0.0000, Gates = 23, Depth = 22
on) = 1.990, Fidelity = 0.278, Entropy = 29.2137, Purity = 0.0000, Gates = 26, Depth = 22
```

Results

- Protocol = teleport
- Δt = κ (0,κ); mimics tuning
- Control, decoupled, coupled

Measuring:

- Photon Exp ↓
- Fidelity ↑
- Entropy ↓
- Purity ↑
- Gate Count ↓
- Depth ↓



Rank & Grading: SSWM Coupler

Protocol	Grade	Reason
1. phase_rotation_chain		High fidelity, low entropy, non-zero purity
2. multi_squeezed_bscoupler		Best fidelity for squeezed multi-mode, stable photons
3. displacement_entangle		Usable fidelity, moderate entropy
4. simple_squeezing		Consistent but low fidelity, entropy reasonable for squeezing
5. teleportation		Very low fidelity for its use case, no purity, high entropy

Verdict:

The microring functions as a ***promising*** tunable coupler, showing ***viable integration*** into photonic quantum circuits, though its effectiveness depends on ***improved fidelity and state purity.***