

Supplementary Information for

Ultra-Compact Integrated Photonic Logic Chip

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S1. Details for inverse design

S1.1 Adjoint method

We define the objective function of our inverse design process for the device as the overlapping integrals of the output mode fields and normalized target output modes in the cross-shaped output waveguide. The objective function is defined as

$$f = \frac{|\iint \text{Re}[E_{\text{output}}(y', z') \times H_{\text{target}}^*(y', z') + E_{\text{target}}(y', z') \times H_{\text{output}}^*(y', z')] dydz|^2}{\iint \text{Re}[E_{\text{target}}(y', z') \times H_{\text{target}}^*(y', z')] dydz} \quad (S1)$$

where (y', z') represents an arbitrary point in the output port plane, $E_{\text{target}}(y', z')$, $H_{\text{target}}(y', z')$ represent the electric and magnetic fields of the target output mode and $E_{\text{output}}(y', z')$, $H_{\text{output}}(y', z')$ represent the electric and magnetic fields of the actual output mode. The asterisk above means complex conjugation.¹

In the first stage of optimization, the iteration is carried out using the gradient descent algorithm Adjoint Method. The refractive index of a material unit in the design region continuously change between the refractive index of Si and air.

First of all, the objective function we have defined represents the performance of our device as the mode transmission at 1530 nm-1570 nm. When changing the relative permittivity $\varepsilon(x, y)$ of a unit at (x, y) in the design region, we introduce a variation of the electric dipole moment, leading to a variation of the output electromagnetic field simultaneously. Target output modes are pre-defined and keep unchanged during the optimization process. Besides, $H_{\text{output}} \propto E_{\text{output}}$, so the objective function can be expressed as

$$f = f(E_{\text{output}}(\varepsilon)) \quad (S2)$$

where ε is the permittivity distribution of the design region. The total change of the output field will be a superposition of variations caused by every unit in design region. We use adjoint method to maximize the transmission of the target light field and ε^k is the permittivity of the k th iteration. The gradient is multiplied by the weights α and then added to the permittivity of the k th iteration to get the permittivity of the $(k + 1)$ th iteration:

$$\varepsilon^{k+1} = \varepsilon^k + \alpha \frac{\partial f}{\partial \varepsilon^k} \quad (S3)$$

Secondly, the gradient $\frac{\partial f}{\partial \varepsilon^k}$ is calculated by the equation below:

$$\frac{\partial f}{\partial \varepsilon^k} = \frac{\partial E}{\partial \varepsilon^k} \frac{\partial f}{\partial E} \quad (S4)$$

From Maxwell's equations, we can get

$$\nabla \times (\nabla \times E) - \omega^2 \varepsilon \mu_0 E = i\omega \mu_0 J \quad (S5)$$

where ω is the frequency of the signal light, μ_0 is the vacuum permeability. Eq.(S5) can be written as

$$AE = i\omega \mu_0 J \quad (S6)$$

where A represents the operator $\nabla \times (\nabla \times) - \omega^2 \varepsilon \mu_0$.

Calculating the partial derivative of both sides of Eq.(S6), we get the following equations,

$$\frac{\partial A}{\partial \varepsilon^k} E + A \frac{\partial E}{\partial \varepsilon^k} = 0 \quad (S7)$$

$$\frac{\partial E}{\partial \varepsilon^k} = A^{-1} \frac{\partial A}{\partial \varepsilon^k} E = A^{-1} \cdot (-\omega^2 \mu_0) \cdot E \quad (S8)$$

Then we can use Eq.(S8) to substitute $\frac{\partial E}{\partial \varepsilon^k}$ in Eq.(S4) for E , which is the propagation field distribution of the original source over the designed region.^{2,3}

$$\frac{\partial f}{\partial \varepsilon^k} = -\omega^2 \mu_0 A^{-1} \frac{\partial f}{\partial E} E \quad (S9)$$

We assume that there is another source E' satisfying the following equation to substitute $\frac{\partial f}{\partial E}$,⁴

$$AE' = i\omega \mu_0 J' = \frac{\partial f}{\partial E} \quad (S10)$$

Then Eq.(S9) can be written as

$$\frac{\partial f}{\partial \varepsilon^k} = -\omega^2 \mu_0 E' E \quad (S11)$$

We consider E' as the propagation field distribution of adjoint light source over the designed section. Then the variation in the objective function f as the variation of ε can be expressed as

$$\frac{\partial f}{\partial \varepsilon(x, y)^k} = -\omega^2 \mu_0 E'(x, y) E(x, y) \quad (S12)$$

Thirdly, we perform two simulations, including one forward simulation with the

original source input and the adjoint simulation with the adjoint source input. We only enable the input source to get the propagation field distribution E and then we only enable its adjoint source at output port to get the propagation field distribution E' so we can calculate $\frac{\partial f}{\partial \varepsilon^k}$. As the two field distributions E, E' have been collected and then we can get the gradient of the objective function for the permittivity.

The second step is partial-binarization optimization and the refractive index of the material units in the design region is controlled according to the bias factor β which increases gradually to achieve binarization⁵⁻⁷

$$\varepsilon_i = \varepsilon_{min} + \frac{\tanh(\beta\eta) + \tanh(\beta(z_i - \eta))}{\tanh(\beta\eta) + \tanh(\beta(1 - \eta))} (\varepsilon_{max} - \varepsilon_{min}) \quad (S13)$$

In the end, ε_i becomes either the value of the refractive index of Si or air.

S1.2 Characterization of Inverse designed devices

We designed two 50:50 beam splitters of different sizes, one beam coupler, and one waveguide cross using the adjoint method. In our design, the width of the input and output waveguides is 0.5 μm , which means the cross-sectional dimension of the waveguide is 500 nm $\times$ 220 nm. For Splitter 1, the size of the inverse design region is 3.2 μm $\times$ 10 μm and the gap between two output waveguides is 2 μm . For Splitter 2, the inverse design region measures 1.8 μm $\times$ 3.6 μm and the gap between two output waveguides is 1 μm . The geometric shapes of the two optimized beam splitters and the electric field propagation at 1550 nm are shown in Fig. S1a-1d and the transmittance of the upper and lower ports of the two beam splitters is presented in Fig. S1e. It can be observed that both beam splitters achieve the 50:50 beam splitting function excellently, with Splitter 1 exhibiting a negligible additional loss of 0.061 dB and Splitter 2 a loss of 0.221 dB. Our inverse design scheme is suitable for the design of low-loss 50:50 beam splitters of various sizes, thereby meeting the design requirements of arbitrary sizes for connection positions in photonic integrated chips.

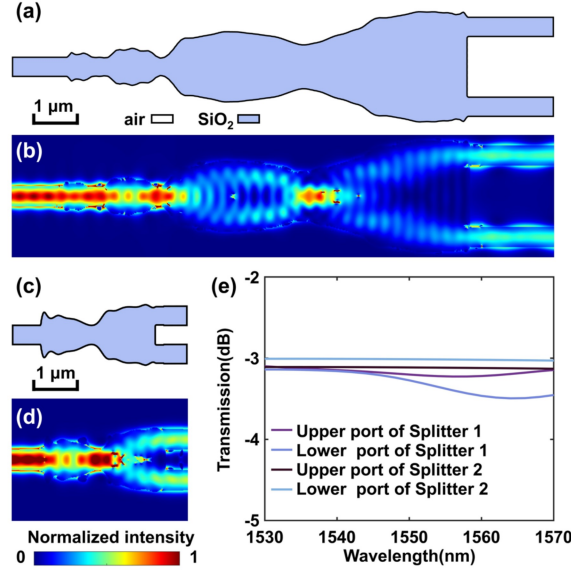


Figure S1. Inverse designed Splitters. Splitter 1: **a.** Detailed schematic of the index profile. **b.** The intensity distribution of propagation fields. **Splitter 2:** **c.** Detailed schematic of the index profile. **d.** The intensity distribution of propagation fields. **e.** Transmission spectrums of the two splitters.

For the beam coupler, the size of the inverse design region is $2\ \mu\text{m} \times 1.8\ \mu\text{m}$, and the output waveguide spacing is $1\ \mu\text{m}$. The geometric shape of the optimized beam coupler and the electric field propagation at $1550\ \text{nm}$ are shown in Fig. S3a and S3b, while the transmittance of the two output ports is presented in Fig. S3c. For the waveguide cross, the inverse design region measures $4\ \mu\text{m} \times 4\ \mu\text{m}$. The geometric shape of the optimized waveguide cross and the electric field propagation at $1550\ \text{nm}$ are illustrated in Fig. S3d and S3e, and the transmission transmittance of the two vertical and horizontal branches is displayed in Fig. S3f. It can be observed that the waveguide cross does not affect the respective transmission of the two branches. Serving as connection components in the photonic integrated chip, these structures can effectively reduce the overall footprint and enhance the chip integration density, as shown in Fig. S3g-S3i.

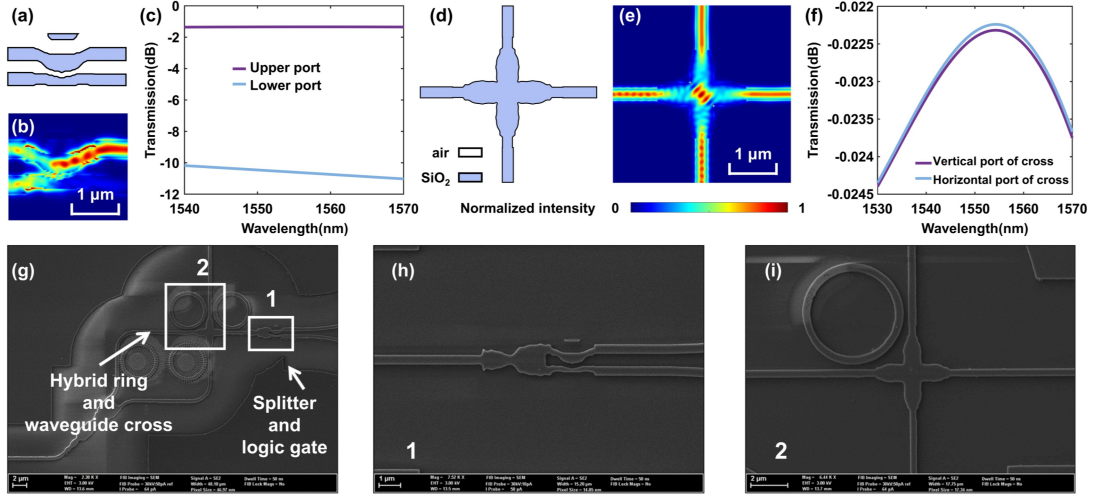


Figure S2. The inverse designed beam coupler and the waveguide cross. The waveguide cross: **a.** Detailed schematic of the index profile. **b.** The intensity distribution of propagation fields. **c.** Transmission spectrum. The beam coupler: **d.** Detailed schematic of the index profile. **e.** The intensity distribution of propagation fields. **f.** Transmission spectrum. **g.** The SEM image of the entire chip with inverse designed devices. **h.** The SEM image of Splitter 2 and the beam coupler. **i.** The SEM image of the hybrid Bi_2Te_3 ring and the inverse designed waveguide cross.

The evolution curves of FOM during the entire inverse design iteration process of the four devices are shown in Fig S3a to S3c, clearly showing how FOM changes with the increase of iterations until it converges to the optimal value. The FOM in all cases exhibits a rapid initial increase followed by a gradual convergence with minor oscillations. The exact number of iterations and the total design time required to achieve the optimal design are shown in Table S1. The simulations were carried out on a workstation equipped with dual Intel Xeon Platinum 8383C CPUs, 256 GB RAM, and an NVIDIA RTX 4080 GPU and the total design time for each device depends on the device complexity and simulation settings.

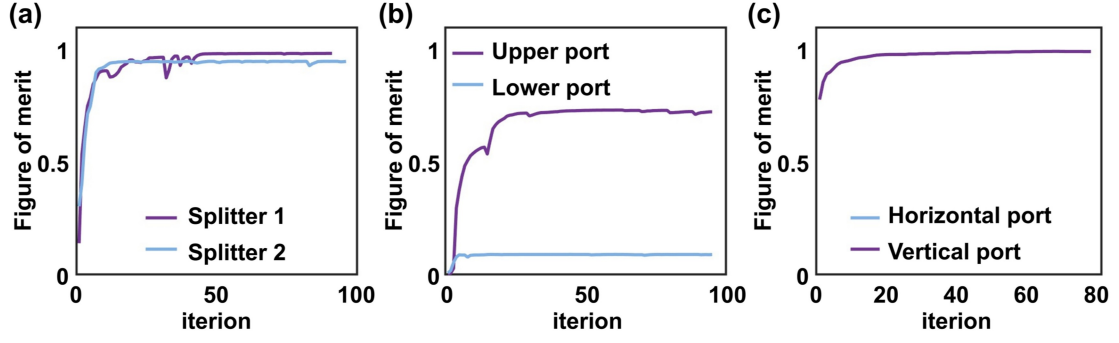


Figure S3. The curves of Figure of merit. a. Two 50:50 splitters with different footprints. b. The logic gate. c. The waveguide cross.

Table S1. Iterations and design time required for the inverse-design devices

devices	number of iterations	total design time
Splitter 1	91	20 h 36 min
Splitter 2	96	8 h 25 min
Gate	94	3 h 17 min
Cross	77	5 h 6 min

S1.3 Comparisons of the conventional layouts and the inverse designed layouts.

We design a traditional designed 50:50 splitter as shown in Fig S4a which can also achieve a 50:50 power splitting ratio with comparably low loss as shown in Fig. S4b, its footprint is significantly larger than those of the two inverse-designed splitters. The detailed comparisons are shown in Table S2.

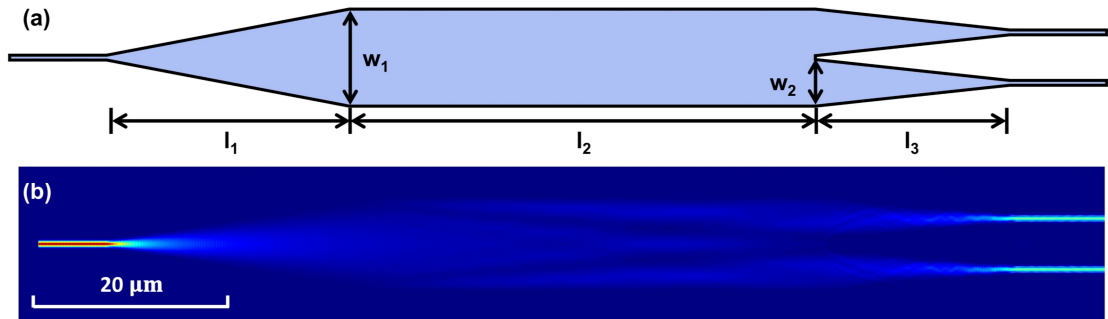


Figure S4. Traditional designed 50:50 splitter. **a.** Detailed schematic of the index profile. **b.** The intensity distribution of propagation fields.

Table S2. Comparisons of the traditional designed splitter and the inverse designed splitters

Single device footprint						Loss
Inverse designed splitter 1						0.221 dB
$2\ \mu\text{m} \times 1.8\ \mu\text{m}$						
Inverse designed splitter 2						0.061 dB
$10\ \mu\text{m} \times 3.2\ \mu\text{m}$						
Traditional designed splitter	l_1	l_2	l_3	w_1	w_2	
	25 μm	48 μm	20 μm	10 μm	4.8 μm	0.190 dB
	$93\ \mu\text{m} \times 10\ \mu\text{m}$					

As shown in Fig. S5a to S5c, we further demonstrate the simulations that conventional photonic components based on standard waveguide layouts typically require a minimum spacing of several micrometers to suppress crosstalk and ensure stable operation. As shown in Fig. S5d, the transmission at the target wavelength 1550 nm, which is corresponding to the original micro-ring resonance, varies as the horizontal separation L between the micro-ring resonance center and the splitter endpoint decreases. It can be observed that, for the conventional splitter, the transmission spectrum stabilizes only when L exceeds approximately 7 μm .

In contrast, the inverse-designed splitter enables strong light confinement and engineered mode evolution within a compact region. As a result, the transmission spectrum remains stable when L exceeds 2 μm as shown in Fig. S5e. This allows the device pitch to be reduced to much smaller spacing of 1.5 μm while maintaining reliable optical performance.

These results quantitatively demonstrate that inverse design is a necessary approach to reduce the footprint and achieve ultra-compact integration scale.

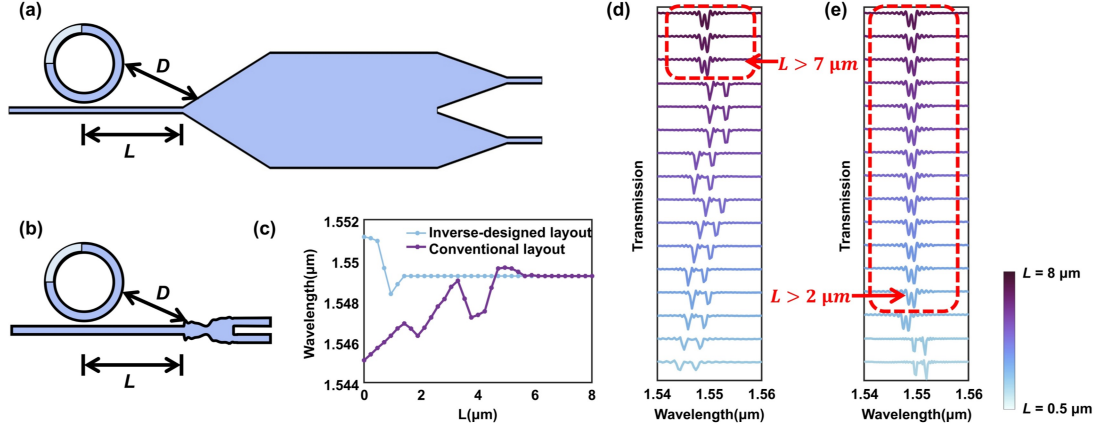


Figure S5. Simulation results of the conventional layouts and the inverse designed layouts. The scheme of the conventional layouts with a micro-ring and a splitter. L denotes the horizontal separation between the micro-ring resonance center and the splitter endpoint. a. Conventional layouts. b. Inverse designed layouts. The intensity distribution of propagation fields. c. Curves of the micro-ring resonant wavelength as L varies. d. Transmission spectrums of the micro-ring resonance in the conventional layouts as L varies. The spectrums become stable when $L > 7 \mu\text{m}$. e. Transmission spectrums of the micro-ring resonance in the inverse designed layouts as L varies. The spectrums become stable when $L > 2 \mu\text{m}$.

Table S3. Comparisons of the conventional designed layouts and the inverse designed layouts

	Layout area	L	D
Inverse designed layouts	Less than $10 \mu\text{m} \times 10 \mu\text{m}$	$2 \mu\text{m}$	$\sim 1.5 \mu\text{m}$
Conventional layouts	About $90 \mu\text{m} \times 10 \mu\text{m}$	$7 \mu\text{m}$	$\sim 5.5 \mu\text{m}$

S1.4 Fabrication process flow of the integrated photonic chip

In the fabrication process of the integrated photonic chip the passive photonic circuit, including the waveguides, resonators, and inverse-designed structures, is first defined by lithography and ICP etching. The Bi_2Te_3 layer is then introduced by PLD deposition and further patterned by FIB processing to achieve accurate alignment with the underlying silicon structures. After the passive chip is completed, the sample is cleaved

and polished, followed by precise alignment and butt coupling of the waveguide-output micro-laser to the chip facet. Finally, the electrical and optical ports are encapsulated to realize the packaged hybrid photonic device.

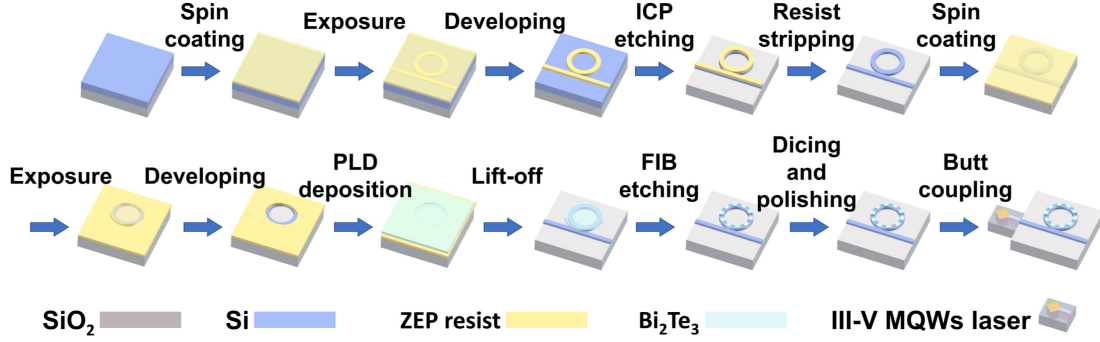


Figure S6. Fabrication process flow of the integrated photonic chip.

S2. Fabrication process and characterization of the micro-laser

Fig. S7a shows the Fabrication process of the unidirectional-emission circular-side octagon micro-lasers. The micro-lasers with the side length of 8 μm , deformation of 0.2 μm and 2- μm -wide waveguide are fabricated using the AlGaInAs/InP epitaxial wafer. The active region consists of six compressively strained 6-nm-thick quantum wells and seven 9-nm-thick barrier layers, sandwiched between two 100 nm AlGaInAs separate confinement layers. Contacting photolithography and ICP etching are employed to transfer the micro-cavity patterns onto the SiO₂ layer. Smooth and steep sidewalls with a deep etching depth of 4.7 μm are achieved by ICP process again with the patterns SiO₂ layer as the mask for guaranteeing significant optical confinement. A 200 nm SiN layer is deposited for better adhesion after ICP etching, and a BCB layer for planarization is used to laterally confine micro-cavities. Afterward, a contact window is opened on the top of micro-cavity, and a Ti/Pt/Au p-electrode is deposited by e-beam evaporation and lift-off process, and an Au/Ge/Ni metallization layer as n-electrode is deposited by magnetron sputtering after lapping down the laser wafer to a 120 μm thickness.

Fig. S7b presents the SEM image of the sidewall smooth and steep sidewalls with an etching depth of 4.7 μm of the fabricated octagon micro-laser after the ICP etching process and Fig. S7c presents the microscope image of the micro-laser. In order to

facilitate the coupling between the micro-laser and the silicon optical chip, the micro-lasers are cleaved over the output waveguides and bonded on an AlN sub-mount with a matched resistance of $35\ \Omega$. Then the device is mounted on a thermoelectric cooler (TEC) to control the substrate temperature.

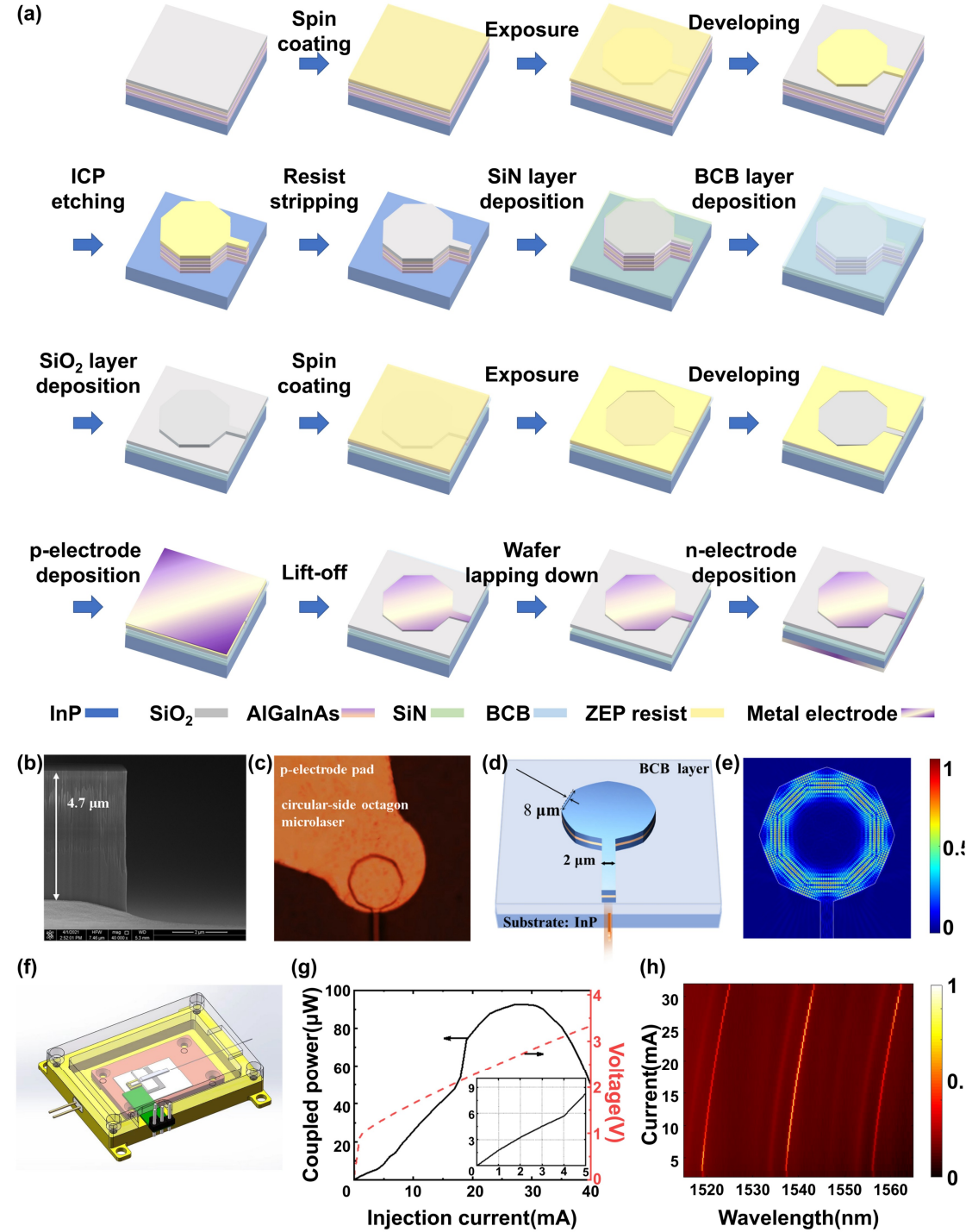


Figure S7. Fabrication process and characterization of the WGM micro-laser. a. Fabrication process flow. **b.** SEM image of the smooth and steep sidewalls of the micro-

laser after the ICP etching process. **c.** Microscopic image of the fabricated unidirectional-emission circular-side octagon micro-lasers with the side length of 8 μm , 0.2 μm deformation, and 2- μm -wide waveguide. **d.** Schematic diagrams of the unidirectional-emission circular-side octagon micro-cavity laterally confined by BCB layer, where the flat side length of the octagon of 8 μm and the deformation parameter δ of 0.2 μm . **e.** Mode magnetic field patterns $|H_z|$ for the fundamental modes. **f.** The configuration of packing chip. **g.** Output power coupled to MMF and applied voltage at 293 K as functions of continuous injection current of the micro-laser. The inset is an enlarged view of the V-I curve near the threshold. **h.** Shifts of the laser spectra as the injection current varies.

The schematic diagram of the unidirectional-emission circular-side octagon micro-cavity is shown in Fig. S7d. The flat side length of the octagon is a , the radius of the circular arc is r , and the deformation parameter δ is the distance between the flat side and the top of arc satisfying $\delta = r - \sqrt{r^2 - (a/2)^2}$. The structure parameters of the circular-side octagon micro-cavity are taken to be $a = 8 \mu\text{m}$, $r = 40 \mu\text{m}$, and $\delta = 0.2 \mu\text{m}$, and the waveguide width is 2 μm . Fig. S7e illustrates the magnetic field ($|H_z|$) patterns of the fundamental mode. Simulation results show that the unidirectional-emission circular-side octagon micro-cavity is experimentally suitable for single-mode operation.

The output power coupled to MMF as shown in Fig. S7f and applied voltage of the unidirectional-emission micro-laser are plotted as functions of the continuous injection current at 293 K in Fig. S7g. The maximum output powers are 93 μW at the injecting current of 29 mA, where the micro-laser suffers from power saturate effect. The threshold current is 4 mA with the threshold current density of 1.3 kA/cm^2 in the inset of Fig. S7f. The series resistor of 20 Ω was estimated from the applied voltage versus the injecting current around 30 mA after subtracting the matching resistance. The output spectra of the octagon micro-laser as the injection current changes is shown in Fig. S7h.

S3. Characterization of the hybrid Bi_2Te_3 -Si micro-ring resonators

We performed the numerical simulation and obtained the TE mode field distributions in the bare Si waveguide and hybrid Bi_2Te_3 -Si waveguide, as shown in Figs. S8a-S8c. It can be observed that after coating the nonlinear material Bi_2Te_3 , since the real part of the refractive index of Bi_2Te_3 is higher than that of Si, the optical field in the hybrid Bi_2Te_3 -Si waveguide shifts toward the upper Bi_2Te_3 layer. However, as the coated Bi_2Te_3 film is only 50 nm thick, most of the field remains confined in the Si waveguide, thereby reducing the loss caused by the saturated absorption of Bi_2Te_3 .

The refractive index of Bi_2Te_3 varies with the applied pump power, ranging from 4.86 to 5.04. Accordingly, we simulated the transmission spectrums of the two micro-ring resonators and the electric field distributions of their TE resonant modes under different pumping intensities, as illustrated in the Figs. S9a-S9i and Figs. S10a-S10i.

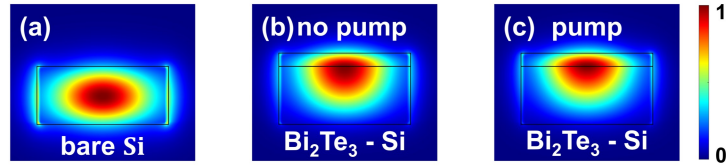


Figure S8. Theoretical results for TE mode field distributions in waveguides. a. in the bare Si waveguide. **b.** in the hybrid Bi_2Te_3 -Si waveguide when no pump. **c.** in the hybrid Bi_2Te_3 -Si waveguide when pumped.

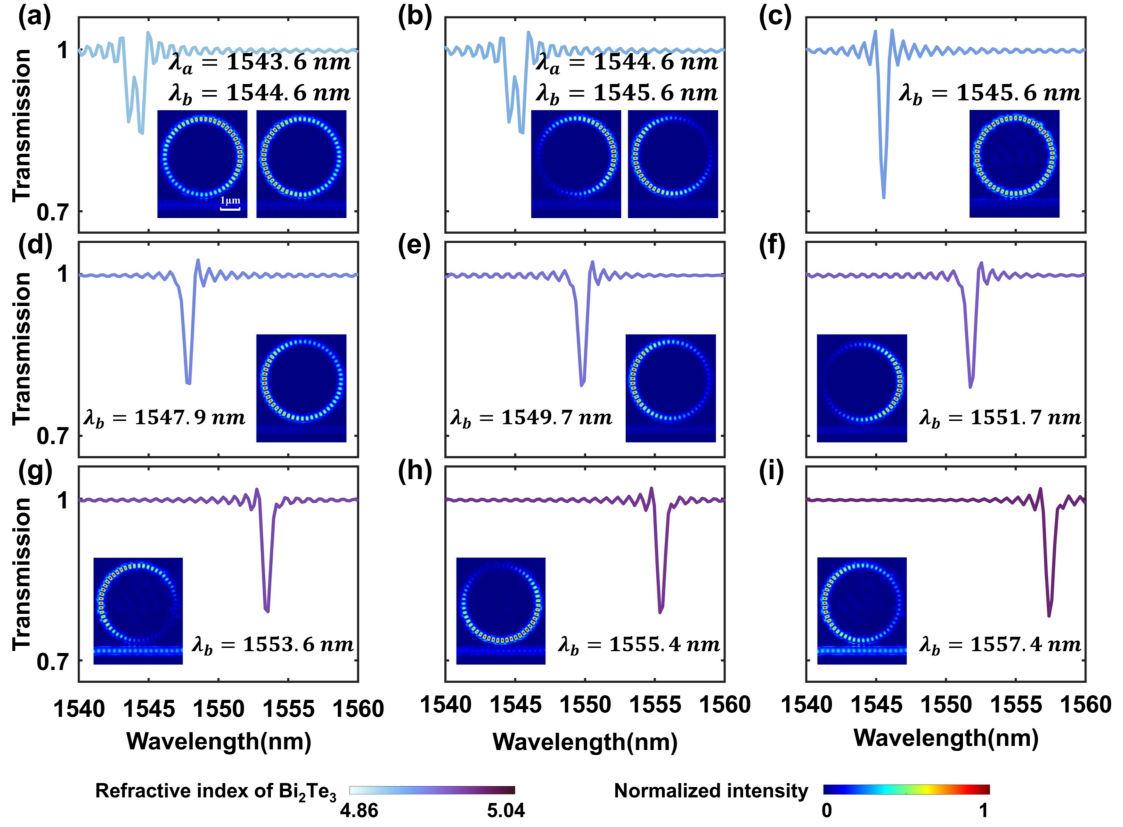


Figure S9. Theoretical results for transmission spectrums and the electric field distributions of the anti-PT symmetric resonator. a. No pump. b-i. Pumped. b to i: Pumping power gradually increases, and the effective refractive index increases correspondingly.

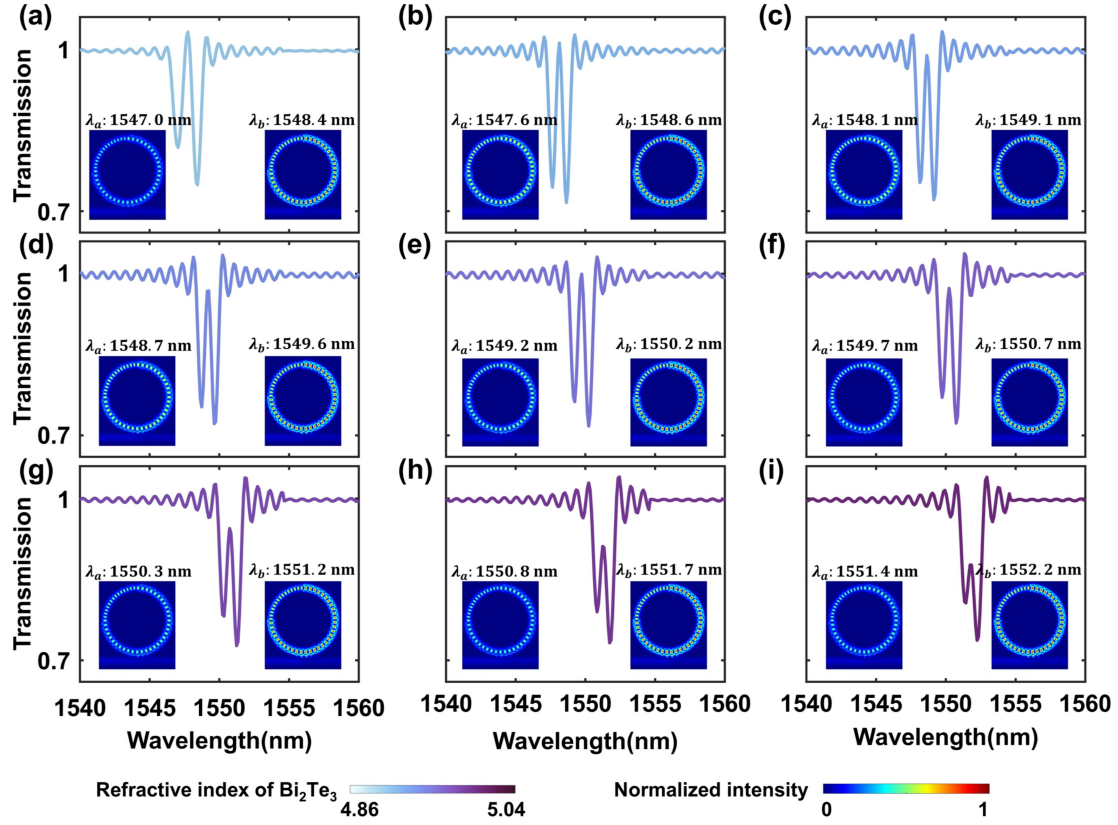


Figure S10. Theoretical results for transmission spectrums and the electric field distributions of 1/4-perimeter coated micro-ring resonators. a. No pump. **b-i.** Pumped. **b to i:** Pumping power gradually increases, and the effective refractive index increases correspondingly.

The different relative positions between the hybrid Bi_2Te_3 -Si micro-ring resonators and the waveguides arise deviations in coupling effects arise and slight shifts in resonance wavelengths. For anti-PT-symmetric resonator, we assume the rotation angle between the periodically coated Bi_2Te_3 nonlinear material and the waveguide coupling points is θ and the initial angular position of the resonator is 6.71° . A shift of approximately 1 nm in the resonance wavelength occurs when the coupling position varies, shown in Fig. S12a. Similarly for the 1/4-perimeter coated micro-ring resonators, 1/4-perimeter coated micro-ring resonators rotated by θ produce different coupling effects with the underlying coupling waveguide, corresponding to distinct transmission spectrums and modulation performances, as shown in Fig. S11b.

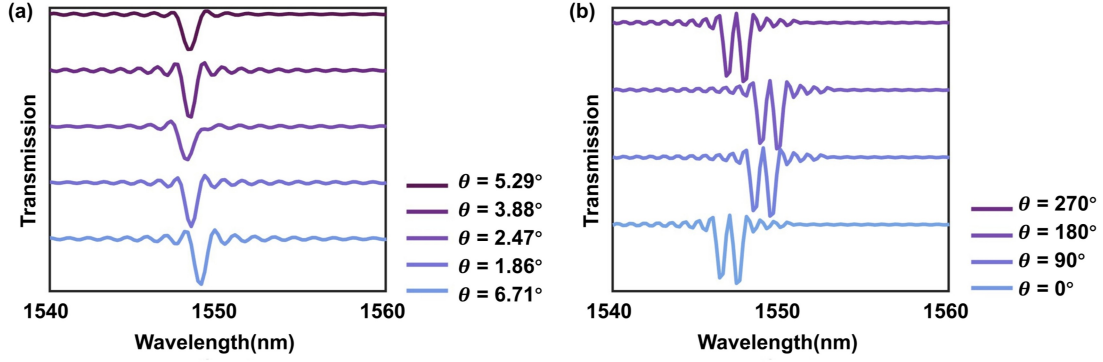


Figure S11. Theoretical results of hybrid Bi_2Te_3 -Si micro-ring. Transmission spectrums and resonance wavelength shifts under at different rotation angles. a. The anti-PT symmetric resonator. b. The 1/4-perimeter coated micro-ring resonator.

S4. Transmission spectrum of Port 3 on the proposed photonic chip

As shown in Fig. 4, three output ports are employed, where Output Ports 1 and 2 serve as the 2-bit logical outputs, while Output Port 3 is introduced as a reference port corresponding to the logical '0' level. And the experimental measurement transmission spectrums of Output Port 3 when the logical outputs of Output Ports 1 and 2 are '00', '11', '10', '01' respectively are shown in Fig S12.

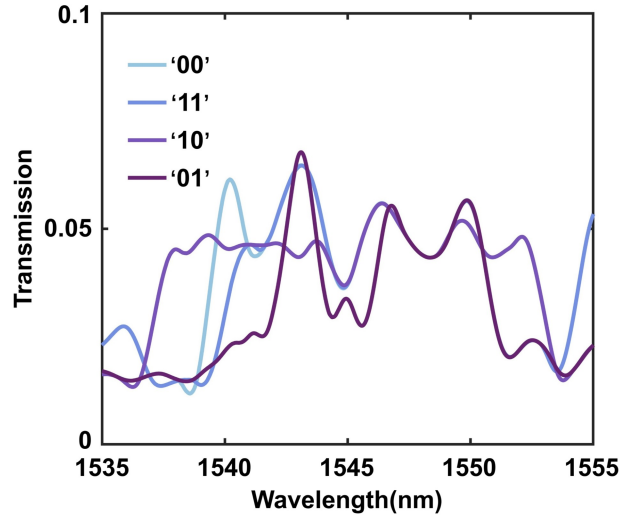


Figure S12. Transmission spectrums of Output Port 3.

To realize a stable and reliable reference, Output Port 3 is implemented using a cascaded structure consisting of a 1×2 power divider followed by a 2×2 coupler. In this

configuration, the optical signal is first split into two branches. One branch is directed to Output Port 2 for logic output, while the other branch is routed to Output Port 3 to generate a reference signal.

The use of the 1×2 power divider ensures that both the logic output and the reference signal originate from the same input source, thereby maintaining identical initial conditions. Furthermore, the subsequent 2×2 coupler provides additional control over the signal distribution and offers a scalable architecture for future extension. By introducing tunable or cascaded coupling stages, the structure can be adapted for more complex logic operations and multi-functional photonic circuits.

S5. Comparisons of the integrated optical logic device.

In the Table S4, we briefly summarize the schemes for integrated optical logic gates and device, covering different integration platforms and various logic operation implementations, including all-optical logic gates, electro-optical hybrid logic devices, and logic circuits based on resonant cavities.

The advantages and innovations of our proposed integrated architecture for on-chip logic operations include: (1) Inverse design method is used to reduce the footprint and inter-component separations and ensure the device performance at the same time. (2) The demonstrated all-optical modulation and switching is based on the reliable integration of the whispering-gallery-mode micro-laser and the photonic chip. (3) Silicon-based micro-ring resonators is coated with the nonlinear material Bi_2Te_3 which has a considerable nonlinear effect to enhance response of the hybrid structure under different pumping conditions.

Table S4. Comparisons of the integrated optical logic device.

Ref	Scheme	Function	Footprint	Speed	Material	Mechanism
8	Micro-ring resonators	XOR, AND, OR, NOT, NOR, NAND, XNOR	$\sim 17 \mu\text{m} \times 1.5 \mu\text{m}$	$\sim 5.2 \text{ ps}$	Si	Resonance tuning
9		2-bit adder 3-x Logic	$\sim 30 \mu\text{m}^2$	ns	Si and phase change material	Electrically induced phase change
10		NAND, XOR, OR, NOT	$\sim 33 \mu\text{m} \times 24 \mu\text{m}$	ms	Si and MEMS	Electrically driven mechanical resonance tuning
11	Waveguide	Logic switch	$\sim 2 \mu\text{m} \times 5 \mu\text{m}$	ps scale	Al_2O_3 grating filled with a π -conjugated polymer	Exciton-polariton condensation at ambient conditions
12		AND, NAND, OR, NOT, NOR, XOR, XNOR	$\sim 10 \mu\text{m} \times 50 \mu\text{m}$	$\sim 4 \text{ ns}$	Si waveguide coated with BP and MoS_2	linear coupling
13		XOR, AND, OR, NOT, NOR, NAND, XNOR	μm -scale	ps	Ψ-shaped silicon waveguides	Interference
14	Photonic crystal	NOT, XOR, XNOR	$\sim 85.8 \mu\text{m}^2$	8.33ps	Si	Topological edge states and interference
15		AND, OR, NOT, NOR, NAND, XOR, XNOR	$\sim 77.13 \mu\text{m}^2$	0.7ps		
16		AND, OR, NOT	\	80 fs-2 ps	ZnO microcavity	Polariton condensate and exciton reservoir dynamics
17	Polariton-based resonators	NOR	\	$\sim 1 \text{ ps}$	Organic semiconductor polymer microcavity	Non-ground-state polariton amplification in distributed Bragg reflectors
18	Inverse design	AN, OR, NOT, NOR, NAND, XNOR, XNOR	\	$\sim 10 \text{ ps}$	Liquid-metal Galinstan nanodroplet assemblies	Plasmonic optical-thermal effects
19		OR, NOT, AND, XOR	$\sim 2.4 \mu\text{m} \times 2.4 \mu\text{m}$	$\sim 1 \text{ ps}$	Phase change material	Nonvolatile phase transition
This work	Micro-ring resonators	2-bit logic output	indivial switch: $\sim 5 \mu\text{m} \times 5 \mu\text{m}$ entire logic chip: $\sim 30 \mu\text{m} \times 25 \mu\text{m}$	$< 1 \text{ ps}$	Si and Bi_2Te_3	Kerr effect and resonance tuning

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