Supplemental Document

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On-chip ultracompact multimode vortex beam emitter based on vertical modes: supplement

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On-chip Ultracompact Multimode Vortex Beam Emitter Based on Vertical Modes: supplemental document

This supplement contains:

1. NOTE S1. WAVEGUIDE MODE ANALYSIS SIMULATION SETTINGS

We analyze the waveguide modes by Lumeircal Mode Solutions. As shown in Figure 2(a), we build the Si waveguide on the SiO_2 substrate. The cross-sectional size of the small aspect ratio waveguide is 0.2 µm in height and 1.2 µm in width. The cross-sectional size of the large aspect ratio waveguide is 1.2 µm in height and 0.2 µm in width. The size of finite difference eigenmode solver (FDE) is $4 \times 4 \mu m^2$ and the center of FDE is aligned with the waveguide center. The boundary conditions are all PML. The grid in FDE is $5 \times 5 nm^2$.

2. NOTE S2. TM_0 MODE COUPLING STRUCTURE PARAMETERS

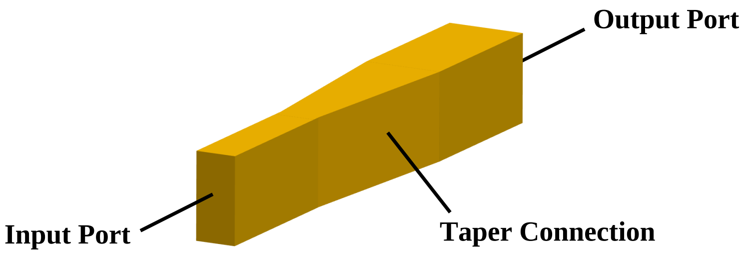

Fig. S1. Schematic diagram of TM_0 mode coupling structure.

Table S1. Parameter values of TM_0 mode coupling structure.

Waveguide Height [μm]	Input Port Waveguide Width [μm]	Output Port Waveguide Width [μm]	Connection Length [μm]
0.820	0.100	0.200	6.000

3. NOTE S3. TM_1 MODE COUPLING STRUCTURE PARAMETERS

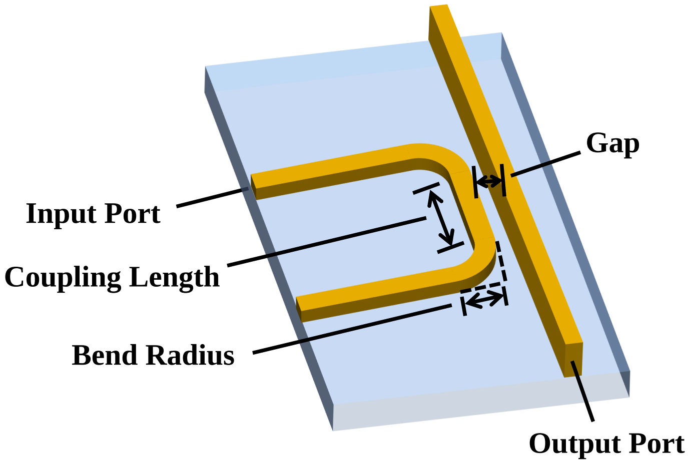

Fig. S2. Schematic diagram of TM_1 mode coupling structure.

Table S2. Parameter values of TM_1 mode coupling structure.

Input Port Waveguide Height [μm]	**Coupling Length** [μm]	**Bend Radius** [μm]
0.399	4.000	1.500
Output Port Waveguide Height [μm]	**Waveguide Width** [μm]	**Gap** [μm]
0.820	0.200	0.190

4. NOTE S4. FOUR-MODE AND FIVE-MODE VORTEX BEAM EMITTER STRUCTURE PARAMETERS

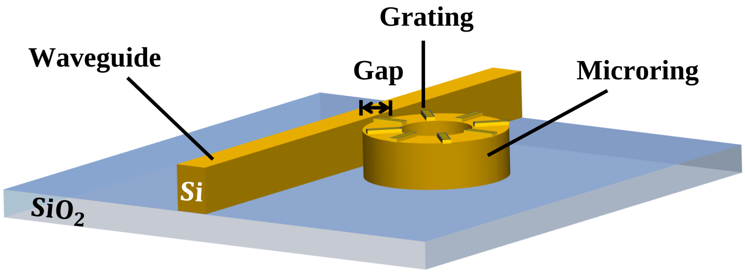

Fig. S3. Schematic diagram of the vortex beam emitter.

Table S3. Parameter values of four-mode and five-mode vortex beam emitters.

	Four-mode Emitter	Five-mode Emitter
Waveguide Width [μm]	0.200	
Waveguide Height [μm]	0.820	0.968
Microring Radius [μm]	1.500	
Grating Length [μm]	0.340	0.310
Grating Height [μm]	0.100	
Gap [μm]	0.150	
Grating Number	15	

5. NOTE S5. MULTIMODE RESONANT WAVELENGTHS ALIGNMENT METHOD

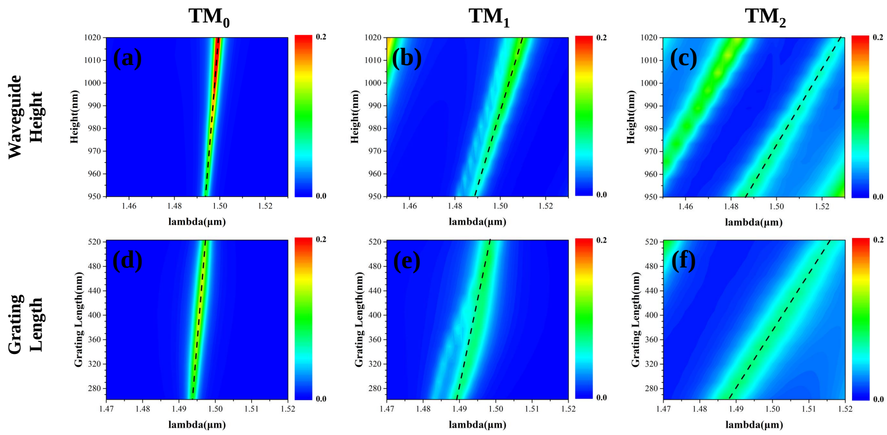

Fig. S4. Multimode resonant wavelengths adjustment method. (a)-(c) Varying the waveguide height, the resonant wavelength changes of TM_0, TM_1 and TM_2 modes. (d)-(f) Varying the grating element length, the resonant wavelength changes of TM_0, TM_1 and TM_2 modes.

As shown in Figure S4, when the waveguide height and grating element length are adjusted respectively, the variation range of resonant wavelengths of the three waveguide modes is different. For the same mode, the change of resonant wavelength caused by adjusting the height of waveguide is larger than that caused by adjusting the length of grating element. Therefore, in our design method , the waveguide height is firstly adjusted to achieve rough alignment of multimode resonant wavelengths. And then the grating element length is adjusted to achieve further alignment of resonant wavelengths. It is worth noting that the waveguide height should be adjusted to ensure that the waveguide is high enough to support the required waveguide modes, but not too high resulting in the introduction of higher order modes. Moreover, Figure S4 shows that the emission efficiency will also be affected when the resonant wavelength is changed .Therefore, the emission efficiency may be sacrificed by the resonant wavelengths alignment.

6. NOTE S6. TM_1 AND TM_2 MODE COUPLING APPROACH IN FIVE-MODE VORTEX BEAM EMITTER

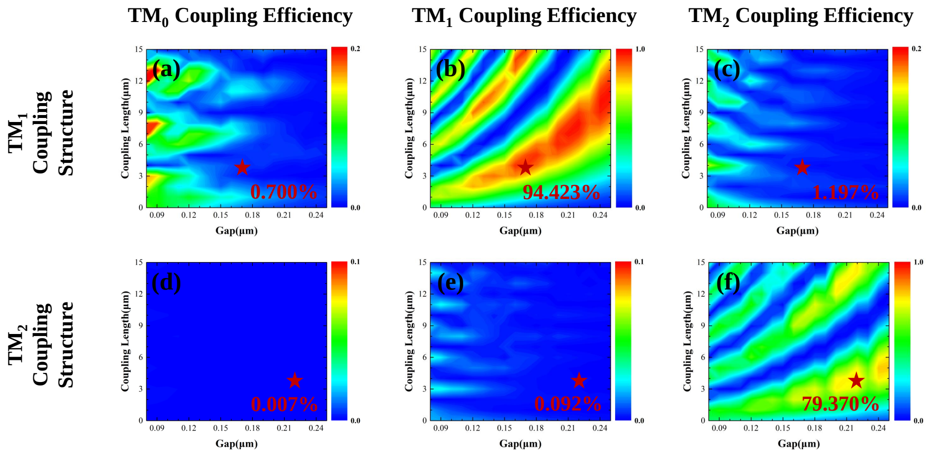

Fig. S5. TM_1 and TM_2 mode coupling approach in five-mode vortex beam emitter. (a)-(c) TM_0, TM_1, TM_2 mode coupling efficiency of TM_1 coupling structure, when the wavelength is 1.49 µm. (d)-(f) TM_0, TM_1, TM_2 mode coupling efficiency of TM_2 coupling structure, when the wavelength is 1.49 µm.

The waveguide height in the five-mode vortex beam emitter is 968 nm. By effective index matching, the height of the input waveguide in the TM_1 mode coupling structure is 475 nm, and the height of the input waveguide in the TM_2 mode coupling structure is 300 nm. According to the parameter sweeps in Figure S5, it can be determined that the gap in the TM_1 coupling structure is 170 nm, and the coupling length is 4 µm. The coupling efficiency of TM_1 mode is 94.423% and the mode purity is 98.031%. The gap in the TM_2 coupling structure is 220 nm, and the coupling length is 4 µm. The coupling efficiency of TM_2 mode is 79.370% and the mode purity is 99.875%.

7. NOTE S7. DISCUSSION OF GRATING ELEMENT POSITIONS

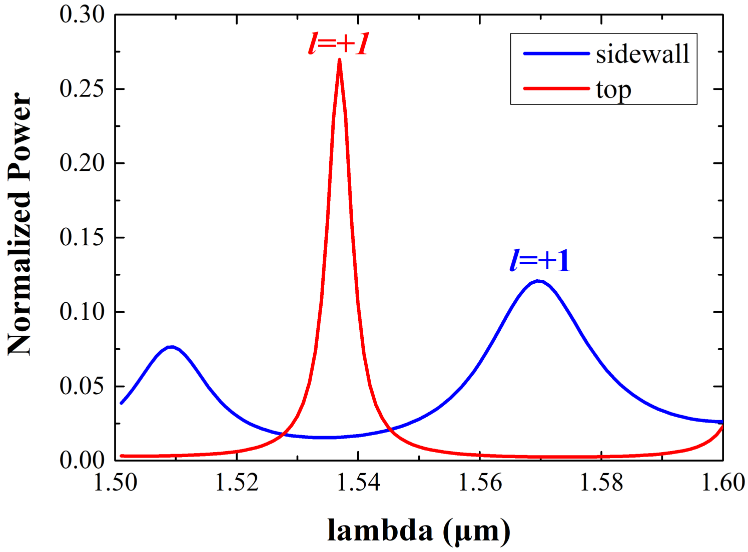

Fig. S6. Emission efficiency of the vortex beam emitter when the grating elements are placed in different positions

As shown in Figure S6, for TM_0 mode, the emission efficiency is about 12% when the grating elements are placed on the sidewall of the microring and about 27% when the grating elements are placed on top of the microring, so we choose to place the grating elements on top of the microring to improve the emission efficiency of the emitter.