Supplemental Document

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High-efficient coupler for thin-film lithium niobate waveguide devices: supplemental document

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The influence of the coupler's parameters to the coupling loss. To research the influence of the coupler's parameters to the coupling loss, firstly we set those parameters to be the optimized values as Fig.2 and Table.1 show in the manuscript. Then we sweep those parameters one by one to get the simulated the coupling loss versus each of them. We sweep the parameters of CLDWG and select optimum ones to make the coupling loss at CS1 (marked in Fig.1) lowest the coupling loss at CS1. As shown in Fig.S1, the simulation result indicates that when values provided in Table.1 are assigned to parameters of CLDWG, the coupling loss at CS1 is about 0.026 dB and 0.027 dB for TE and TM light, respectively.

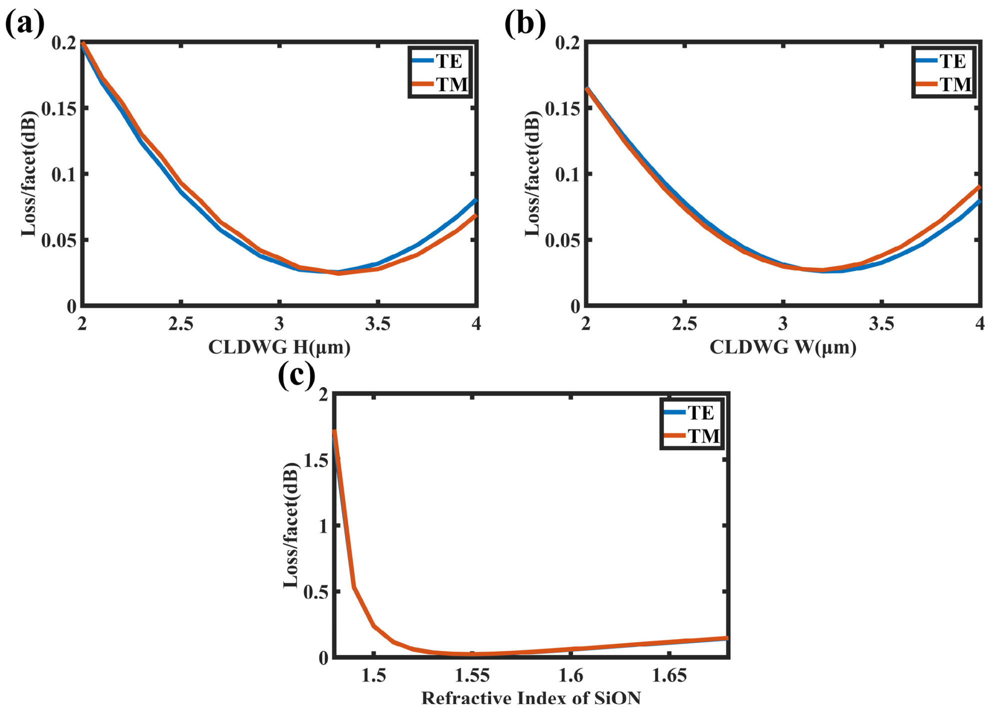

Fig. S1. (a) The simulated coupling loss at CS1 versus CLDWG H (height of cladding waveguide). (b) The simulated coupling loss at CS1 versus CLDWG W (width of cladding waveguide). (c) The simulated coupling loss at CS1 versus refractive index of SiON.

Then, we sweep the key parameters of LN bilayer taper and select optimum ones to make the total coupling loss lowest. The TL 1 and the TW 1 are the key parameters and have great influence on the coupling loss. The loss rises when the TL 1 decreases or the TW 1, namely the tip width of the lower LN inversed taper increases, as Fig. S2 shows. To minimize the coupling loss and the footprint of the coupler, we set the TL 1 to be 100 μm. Besides, couplers with various tip widths (260 nm to 460 nm) of the lower LN inversed taper were fabricated and tested, as shown in Fig. 7(b). The tip with the width small than 260 nm does not contribute to a lower loss, as shown in Fig. S2(b). As for the other parameters, we set them to be reasonable values given in Table.1 and a low loss can be obtained. The final simulated losses of the coupler are 0.07dB and 0.06dB for TE and TM light at 1550nm when TW 1 is set to be 260 nm.

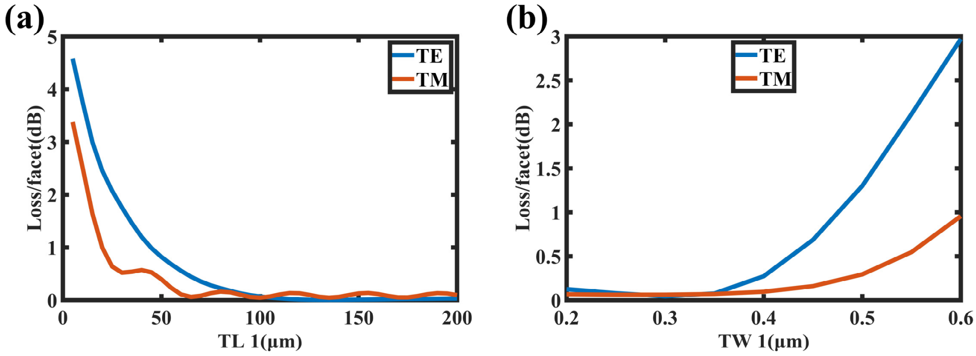

Fig. S2. (a) The simulated total coupling loss versus TL 1 (taper length 1). (b) The simulated total coupling loss versus TW 1 (taper width 1).

Propagation loss of the lithium niobate ridge waveguide. To get the coupling loss of the single edge coupler, the propagation loss of the lithium niobate ridge waveguide is deducted from the insert loss of the whole device which contains two identical edge couplers and a 0.5 cm length of ridge waveguide. To ensure fundamental TE and TM mode operation, the base width and the ridge height of the waveguide are 900 nm and 260 nm, respectively. The propagation loss of the fundamental TE and the TM mode are estimated by the cut-back method, as shown in Fig. S3(a) and Fig. S3(b) respectively. The TE and TM grating couplers are used here. All these waveguides have the same cross section dimension with the waveguide connected with the edge couplers. The propagation losses of the ridge waveguide for TE and TM fundamental modes are estimated to be 0.99dB/cm±0.11dB/cm and 1.54dB/cm±0.13dB/cm, respectively.

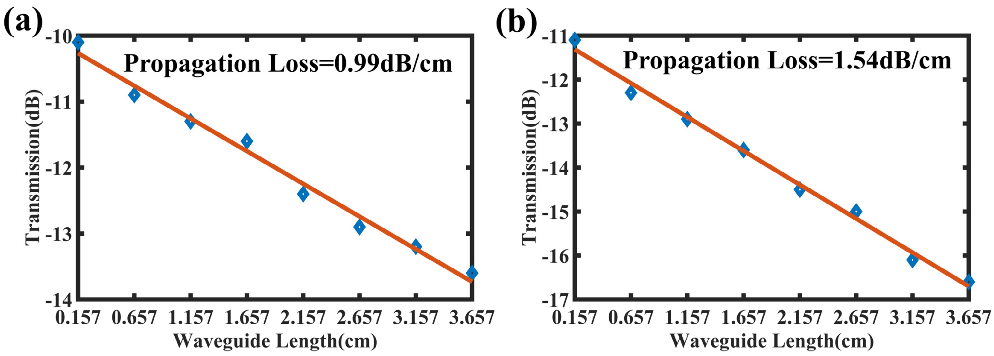

Fig. S3. (a) Fitting to the transmission of the TE waveguide of different length. (b) Fitting to the transmission of the TM waveguide of different length.

Discussion about the slab modes. To confirm that the light dose not transmit from slab modes, we simulate a slab structure which is the same as the coupler by FDTD (Finite Difference-Time Domain) method. The real chip is about twelve millimeters long along the

Z-axis and six millimeters long along the Y-axis. The sizes of the simulation region along Z/Y/X-axis are 40 μm/200 μm/10.4 μm and it is limited by the memory capacity of our computer. As is shown in Fig. S4, the thin film LN (ne~2.12, no~2.20) is on the top of the BOX SiO2 layer (n~1.44) and under the SiON layer (n~1.56). Besides, the silicon substrate is in the bottom and a layer of silicon oxide covers the whole structure. The light can propagate in the form of slab mode in these layers and is divergent along Z-axis lacking the lateral confinement. In simulation, two UHNAFs are used as the excitation and the receiving optical fiber respectively, as shown in Fig. S4(a). All fibers are collinear and closed to the chip. Three different cases are investigated, and the fibers are placed in the centers of the SiON, LN and BOX SiO2 layers respectively, as Fig. S4(b) shows. The TE fundamental mode of UHNAF at 1550nm is used as light source in the simulation and the TM light behaves similarly.

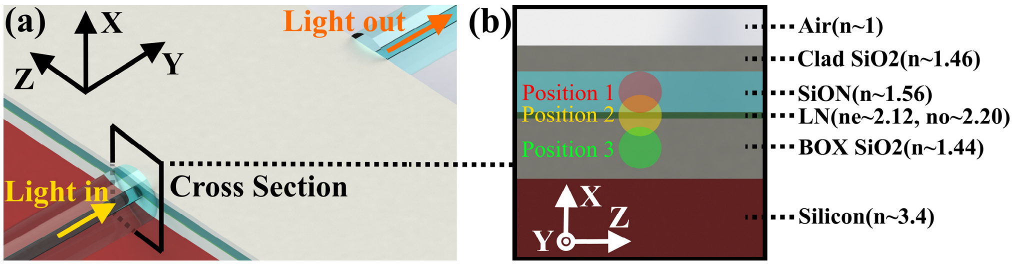

Fig. S4. (a) The schematic diagram of the simulation model to the slab mode. (b) Cross section views of the slab structure.

The top and the cross-section views of the electric intensity spatial distribution when the fiber is placed in position 1, 2 and 3 are shown in Fig. S5(a), (c) and (e), respectively. The full divergence angles of the beams in SiON, LN and BOX SiO2 layers are about 18.3 degrees, 15 degrees and 17.4 degrees, respectively. In these three cases, the lateral sizes of the light spots increase linearly with propagation distance of the light and are calculated to be about 0.97 millimeters, 0.79 millimeters and 0.92 millimeters when the light beam travels six millimeters. The mismatches as well as the coupling losses between those output light spots and the modes of the receiving fiber is also increase linearly with propagation distance of the light. Because the loss is huge, the transmission from the slab modes can be neglected. Besides, we simulate the coupling losses versus the light transmission distance in the slab along Y-axis, as shown in Fig. S5(b), (d) and (f). The losses reach to about 10dB/11dB/17dB when the slab is 200 μm long along the Y-axis. The difference between the raw data and fitting result is derived from the multimode interference. The larger slope shown in Fig. S5(f) is derived from the absorption of the silicon substrate. According to the fitting results, it is expected that the losses will be huge when the slab is six millimeters long along the Y-axis. In conclusion, the light transmitting from slab modes can be neglected.

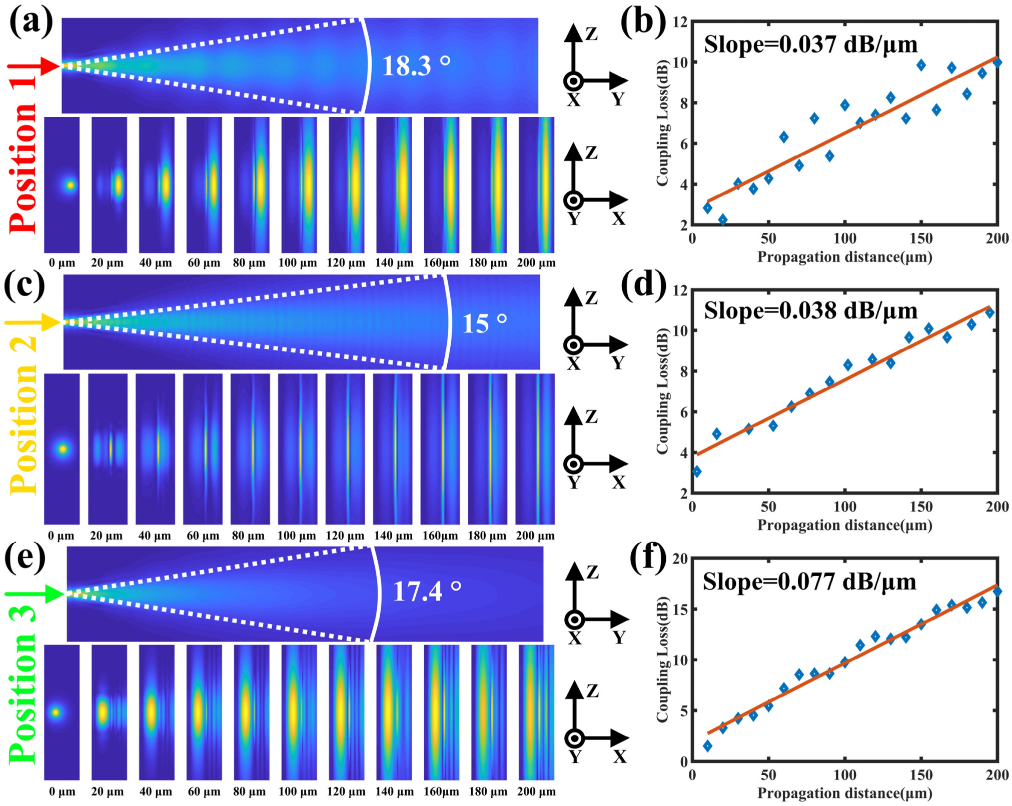

Fig. S5. (a) The top and the cross-section views of the electric intensity spatial distribution when the fiber is placed in position 1. (b) The coupling losses versus the light transmission distance in the slab along Y-axis when the fiber is placed in position 1. (c) The top and the cross-section views of the electric intensity spatial distribution when the fiber is placed in position 2. (d) The coupling losses versus the light transmission distance in the slab along Y-axis when the fiber is placed in position 2. (e) The top and the cross-section views of the electric intensity spatial distribution when the fiber is placed in position 3. (f) The coupling losses versus the light transmission distance in the slab along Y-axis when the fiber is placed in position 3.