Supplementary Information: Low-insertion-loss femtosecond laser inscribed 3D high-density mux/demux devices

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1. Fabrication process of 19-channel mux/demux

In this section, we outline the detailed fabrication process and parameters of the femtosecond laser direct writing system.

A Pharos femtosecond laser source based on Ytterbium-doped laser medium is applied in the fabrication process. Such a femtosecond laser source possesses a center wavelength of 1030 nm, a frequency doubling wavelength of 515 nm, a pulse width of 234fs, a highest pulse energy of 1mJ and an adjustable repetition rate from 50kHz to 1MHz. The femtosecond laser beam propagates through several free-space optics including a half-wave plate, a Grant Taylor prism, a slit, and is then focused into the sample through an objective lens. Free-space optics applied here are capable of tailoring the femtosecond laser beam in many degrees of freedom, that is, controlling its polarization, pulse energy, beam size and so on. During the fabricating process, the glass sample is placed on a high-precision electronically controlled XYZ air-bearing stage for translation. The electronically controlled XYZ stage contains a horizonal (XY) resolution of $0.1\mu\text{m}$ and a vertical resolution of $1\mu m$. During the fabrication process, parameters of the sample translation are controlled by a computer, so that the writing speed, direction and depth of focus can be adjusted. Utilizing a LED lighting system and a visible CCD, the femtosecond laser direct writing process is monitored in real time.

Here we supply a table S1 which summarizes the parameters for fabricating the 19-channel FIFO device. As displayed in Table S1, we choose a laser wavelength of 515nm, pulse width of 234fs and a repetition rate of 100kHz. The objective lens applied in the femtosecond laser direct writing system is a 50X objective with a numerical aperture (NA) of 0.42. The substrate translation speed is set to be 0.4mm/s. Ultraviolet optical quartz glass with a size of 20mm*50mm*1mm is utilized here as the substrate material. In the femtosecond laser direct writing system, a $300\text{-}\mu\text{m}$ slit is used to tailor the femtosecond laser beam so that a 1.5-mm diameter laser beam is obtained before the objective lens. Before the slit, laser beam possesses a pulse energy of 9μJ. While after the slit, laser beam possesses a pulse energy of 0.75μJ. During the fabrication process, in order to improve the magnitude of change in refractive index, four scan times is chosen. After four-times writing, waveguides with a diameter of about $8.5\mu\text{m}$ are inscribed to achieve a $9\mu\text{m}$ mode field diameter. It takes about 80 minutes to fabricate such a FIFO device.

Table S1. Parameters for fabricating the 19-channel FIFO device

Wavelength	515nm	Pulse width	234fs
Repetition rate	100kHz	Objective lens	50X, NA of 0.42
Slit width	300μm	Substrate translation speed	0.4mm/s
Substrate material	Quartz glass	Substrate size	20mm*50mm*1mm
Scan times	4	Mode field diameter	9μm
Pulse energy (before slit)	9 μJ	Pulse energy (after slit)	0.75μJ

2. Characterizing the crosstalk of 19-channel mux/demux

In this section, we show the process for characterizing the inter-core crosstalk of fabricated 19-channel FIFO device.

Figure S1 (a) illustrates the experimental setup for measuring the inter-core crosstalk of fabricated 19-channel FIFO device. Light output from a 1550nm laser is split into 19 branches. The 19 branches of light are connected to a single-mode fiber array (SMFA). Then beams output from the SMFA are coupled into the 19-channel FIFO device. An objective lens and a CCD are applied to record the output intensity profile of the FIFO device. Figure S1 (b) and (c) display the results for characterizing the inter-core crosstalk between the channel under characterizing and other channels. Keeping only Ch1 with light beam input, recording the intensity profile of beam output from Ch1 under different situations can characterize the crosstalk between Ch1 and others. Shown in Fig. S1 (b) is the measured output intensity profile of Ch1 under the conditions of: power of laser: 5.5 dBm and exposure time of CCD: 0.1ms. In this situation, beam output from Ch1 can be seen, but the crosstalk beams output from other channels are too weak to see. Thus, we also record Fig. S1 (c) to further see the crosstalk beam under a condition of: power of laser: 16 dBm, exposure time of CCD: 5ms. In this situation, the crosstalk beam can be recorded via the CCD. Applying the intensity profiles in Fig. S1 (b) and (c), crosstalk between Ch1 and other channels can be evaluated as,

$$XT_{1,i} = 10\lg\left(\frac{I_i}{I_1}\right)\text{-}27.5, \tag{S1}$$

where $XT_{1,i}$ denotes the crosstalk between Ch1 and Chi, I_i corresponds to the total gray scale of the intensity profile of crosstalk beam output from Chi (e.g., total grayscale of the crosstalk beam in Fig. S1 (c) equals to I_2), I_1 denotes the total gray scale of the intensity profile of output from Ch1 (i.e., total gray scale of the beam in Fig. S1 (b)). The -27.5 dB here represents a total 27.5dB laser power difference and CCD exposure time difference.

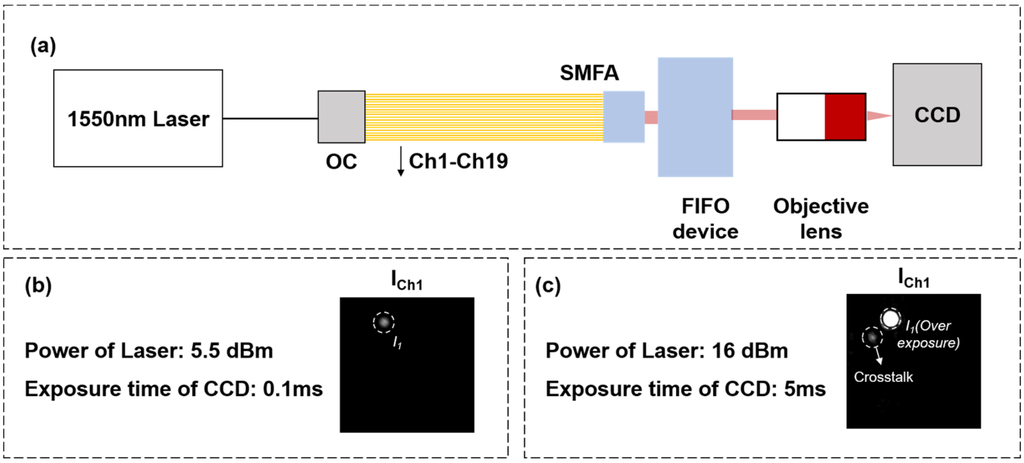

Fig. S1 (a) Experimental setup for characterizing the inter-core crosstalk of the fabricated 19-channel FIFO device. (b)–(c) Measured output intensity profile of channel 1 under different situations: (b) power of laser: 5.5 dBm, exposure time of CCD: 0.1ms; (c) power of laser: 16 dBm, exposure time of CCD: 5ms. OC, optical coupler; SMFA, single-mode fiber array; CCD: charge coupled device.

Shown in Fig. S2 are all the captured intensity profiles for characterizing the 19×19 inter-core crosstalk of the fabricated 19-channel FIFO device. Applying the Eq. (S1), the 19×19 inter-core crosstalk can be evaluated, as shown in Table S2.

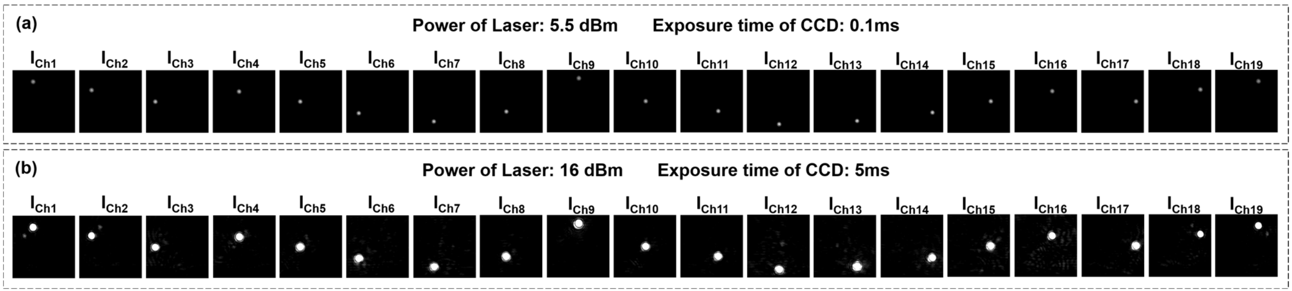

Fig. S2 Measured output intensity profile of all the channels under different situations: (a) power of laser: 5.5 dBm, exposure time of CCD: 0.1ms; (b) power of laser: 16 dBm, exposure time of CCD: 5ms.

Table S2. The whole crosstalk matrix of the tested FIFO device (Unit: dB)

Out \ In	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	0.0	-29.1	-62.6	-41.5	-54.1	None	-43.1	None	-51.9	None	None	None	None	None	None	None	None	None	None
2	-30.0	0.4	-46.5	-46.4	-51.3	-41.1	-43.0	-49.3	None	-51.9	-61.7	-59.3	-46.9	-59.9	None	None	None	None	None
3	-50.0	-32.7	0.7	-47.7	-35.4	-36.8	-42.2	-37.7	None	-49.7	-46.5	-38.2	-41.3	-55.4	-60.2	-58.0	-68.0	None	None
4	-58.9	-37.7	-39.0	0.6	-31.6	-40.1	-45.5	-49.0	-41.6	-39.7	-50.6	-50.7	-45.4	-58.4	-45.3	-34.1	-48.8	-61.0	None
5	-49.2	-45.4	-42.3	-32.3	0.7	-38.9	-40.0	-42.2	None	-36.0	-62.0	None	None	-63.3	-53.7	-56.6	None	None	None
6	-45.1	-39.1	-40.3	-44.4	-34.6	0.5	-30.3	-35.3	-47.7	-47.9	-42.9	-44.1	-43.8	-43.8	-43.2	-41.3	-51.5	-43.1	-50.3
7	-48.9	-55.9	-53.8	-38.7	-47.2	-38.4	0.3	-36.5	-37.4	-38.0	-38.4	-33.8	-38.6	-56.2	-38.1	-50.8	-41.4	-50.2	None
8	-64.8	None	-60.0	-45.2	-42.6	-51.8	-39.6	0.5	-47.2	-37.4	-37.1	None	-45.9	-58.8	-61.8	-43.4	-61.8	-51.8	-64.8
9	-36.4	-43.0	-48.3	-34.6	-50.8	-50.9	-52.9	None	-0.1	-44.2	None	-49.5	None	None	None	-36.2	-54.0	None	-35.4
10	None	None	None	-49.4	-53.6	-44.5	-34.8	-39.4	-52.7	0.2	-48.1	-44.6	None	-57.6	-36.8	-42.9	-49.6	None	-49.8
11	None	None	-56.0	-50.7	-58.7	None	-45.3	-40.8	-54.9	-46.6	0.4	-44.2	-47.9	-44.6	-41.5	-57.7	-47.6	None	-57.3
12	-43.1	-68.0	-46.1	-37.3	-39.4	-35.7	-33.3	-41.1	-41.5	-31.7	-36.0	0.7	-39.3	-50.9	-42.7	-53.1	-46.5	None	-56.0
13	-54.6	-47.0	-43.1	-48.3	-34.5	-53.9	-42.3	-40.6	-38.8	-37.8	-36.1	-32.5	0.5	-33.5	-39.2	-38.9	-39.3	None	-48.9
14	-48.9	-51.6	-45.9	-46.2	-37.6	-48.3	-48.8	-43.9	None	-44.4	-33.6	-42.7	-32.8	0.6	-34.3	-67.9	-37.0	-43.1	-44.9
15	-45.8	-43.4	-45.2	-46.7	-44.5	-54.3	-43.8	-43.0	-55.4	-37.0	-38.2	-32.7	-35.0	-36.2	0.6	-33.2	-37.7	-34.4	-49.0
16	-41.8	-44.0	-38.8	-37.5	-37.3	-37.6	-33.0	-34.7	-33.2	-32.1	-39.6	-38.5	-32.5	-34.4	-32.3	0.0	-33.5	-30.6	-37.4
17	-56.2	None	None	None	-48.1	-51.6	-40.3	-46.9	-53.9	-58.1	-41.9	-38.7	-44.4	-35.8	-37.8	-48.6	0.3	-38.3	-43.3
18	None	None	None	-45.5	None	-46.4	-35.1	-47.1	-62.7	-43.9	-37.2	-43.9	-39.0	-38.1	-43.9	-37.0	-46.9	0.2	-32.5
19	None	None	None	-56.1	None	None	None	None	None	-48.3	-51.7	-44.7	-38.0	-44.6	-55.7	-42.2	-52.5	-30.2	-0.5

The whole crosstalk matrix is normalized based on the value of its first term, that is, the output power of the 1-st channel when the 1-st channel is coupled. For the channels which possess an extremely low power beyond the sensitivity of CCD, we use a 'None' to represent its ultra-low crosstalk. For each channel, we choose the biggest crosstalk between itself and other channels as the crosstalk of this channel, resulting in the crosstalk result in Fig. 6 in the main text.