

Supplementary Materials for

18 Tb/s photonic digital signal processor for real time video image processing

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Device characterization

The transmission and dispersion characterization of the MRR (which is fabricated on high-index doped silica glass platform) are experimentally measured via the MZI (Mach-Zehnder interferometer) method [s1-s2]. Figure S1 shows the schematic diagram of the transmission and dispersion characterization measurement. The MRR transmission, from which Q factor and FSR values are determined, was measured via a tunable laser (Agilent 8164A) swept through wavelength from 1520 nm to 1620 nm and tuning range at a tuning rate of 20 nm/s. The MZI has a path length difference of about 45 m, making the measurement optical frequency sampling resolution approximately 4.6 MHz. The transmission spectra were derived from a balanced photodetector (Thorlabs PDB460C-AC) and observed by the oscilloscope with a memory depth of 50 MPts. The measured and fitting results are shown in Fig. S1 (g) and (h). The power fluctuations of the soliton crystal microcomb were measured over 120 hours (5 days), with the optical spectrum

captured every 15 minutes (Fig. S2 (a)).

Results

The first column of Fig. S3 shows the simulated and experimental results of shaped comb spectra for fractional Hilbert transformer with tunable phase shift from 15° to 75° . A good match between the power of the measured comb lines (red solid lines for the positive tap coefficients and black lines for the negative tap coefficients) and the calculated ideal tap weights (gray dots) was obtained, indicating that the comb lines were successfully shaped. The second column of Fig. S3 shows the shaped impulse response of the fractional Hilbert transform that has 75 wavelengths, or weights, in total. The 3rd to 4th column of Fig. S3 presents the simulated (red dashed curves) and measured (black solid lines) transmission response magnitude and phase. The normalized frequency response and phase response of the fractional Hilbert transformer with tunable orders of 0.166, 0.333, 0.5, 0.667, 0.833, corresponding to phase shifts of 15° , 30° , 45° , 60° , 75° are shown. The last column of Fig. S3 shows the images processed with the fractional Hilbert transformer. The phase shift is tunable which provides better flexibility in image enhancement [s3]. As can be seen, the edges in the image are enhanced, and the experimental results are consistent with the simulation results.

The simulated and experimental results of the shaped comb spectra, temporal impulse response, frequency response and processed image for fractional differentiation with tunable fractional orders from 0.1 to 0.9 are shown in Fig. S4, with the shaped comb spectra in the first column. The wavelength channels for positive and negative taps were separately measured by the OSA. The optical power for each comb line closely matched the designed tap coefficients, verifying the success of our comb shaping procedure. The second column of Fig. S4 shows the shaped impulse response of the fractional differentiation. The measured $|S21|$ curves denoted the power responses of the differentiator, with the operation bandwidth ranging from DC to 18 GHz. As shown in the 3rd and 4th column of Fig. S4, the range of the fractional orders resulted in a close match between the experimental and simulated results in terms of the slope coefficients of the power responses and the phase shift in the measured phase responses. The last column of Fig. S4 illustrates the processed images using the fractional differentiator, where the fractional order was tunable in order to provide better flexibility in edge detection.

Figure S5 shows the simulated and measured results of integral (ie., non-fractional) image processors including a Hilbert transformer with a 90° phase shift, an integrator, as well as first-order differentiator. As predicted in the last column of Fig. S5, the processed image with the Hilbert transformer can be used for edge enhancement, the integrator for motion blur, and the integral differentiator for edge detection. Figure S6 shows a reconfigurable analogue video image processor with operation bandwidth from 4.6 GHz to 36.6 GHz by varying the length of fibre (0.4 km vs 3.96 km) as well as the comb spacing (2-FSR to 8-FSR comb spacing).

We further verified the performance of the image processing function by calculating the root mean square errors (RMSE) between the measured waveforms and the theoretical results (Fig. S7). As shown in Table S1, the RMSEs of Hilbert transformer with tunable phase shift from 15° to 90° are 0.1045, 0.0876, 0.0622, 0.0586, 0.0807, 0.0599, respectively. As for the differentiator with tunable order from 0.1 to 1.0, the RMSEs are 0.0693, 0.0778, 0.0721, 0.0650, 0.0558, 0.0736, 0.0676, 0.0613, 0.0645, 0.0731, respectively. Finally, the RMSE of the integrator is 0.2595.

Chromatic dispersion (CD) compensation

Chromatic dispersion (CD), which causes pulse broadening and limits the performance of the transversal structure, is one of the major impairments in the RF photonic system [s4]. In standard SMF, each optical frequency travels through the fibre at different velocities due to the CD properties of the fibre. It can be shown that the phase changes in the optical sidebands alter the resultant phase of the RF beat signals and the RF power p of the generated radio frequency f_{RF} will vary approximately as [s5]

$$p \propto (\cos \frac{1}{2} \beta_2 \omega^2 z)^2 \quad (3)$$

where p is the RF power, ω is the RF angular frequency, z is the length of standard SMF, and β_2 is the group delay dispersion. Fig. S8 (a) shows the theoretical and measured second order dispersion involved power fading. In an approach, by using the phase modulating capabilities of the WaveShaper, which is capable of producing arbitrary group delay profiles of up to ± 25 ps, it is possible to compensate for group delay ripple (GDR) and significantly improve the accuracy of the system. This compensation is achieved by configuring the WaveShaper to produce an equal but opposite GDR that counteracts the GDR of the system. By employing this approach, we successfully compensated the second-order dispersion (SOD) induced power fading and third-order dispersion (TOD) induced distortion of an integrator (Fig. S8 (b)). Fig. S8 (c) compares the processed images of 0.5 order differentiator with and without dispersion compensation method implemented. As can be seen in Fig. S8 (d), after implementing the dispersion compensation method, the RMSE of the processed signal has been improved from 0.0687 to 0.0558.

Theoretical speed of a scaled up system

Figure S9 shows the video image processor, using the C + L + S bands (with more than 405 wavelengths) and 19 spatial paths, and exploiting polarization. This would yield a speed of 64 GigaBaud $\times$ 8 bits/symbol $\times$ 2 $\times$ 81 $\times$ 19 = 1.575 Petabits/s. In this case the wavelengths would be distributed over 81 processors each have 5 taps in size (so that 81 $\times$ 5 = 405).

References of the Supplementary Materials

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Table S1. Detailed parameters for the massively parallel terahertz video image processor

No .	Computing function	Order	Tap spacing (FSR)	SMF length (km)	No. of taps
1	Differentiation	0.1	9	0.2	1,10,19,28,37
2	Differentiation	0.2	9	0.2	2,11,20,29,38
3	Differentiation	0.3	9	0.2	3,12,21,30,39
4	Differentiation	0.4	9	0.2	4,13,22,31,40
5	Differentiation	0.5	9	0.2	5,14,23,32,41
6	Differentiation	0.6	9	0.2	6,15,24,33,42
7	Differentiation	0.7	9	0.2	7,16,25,34,43
8	Differentiation	0.8	9	0.2	8,17,26,35,44
9	Differentiation	0.9	9	0.2	9,18,27,36,45
10	Hilbert transformation	0.83	3	0.6	46,52,55,58,64
11	Hilbert transformation	0.88	3	0.6	47,53,56,59,65
12	Hilbert transformation	0.94	3	0.6	48,54,57,60,66
13	Hilbert transformation	1	3	0.6	67,73,79,85
14	Hilbert transformation	0.78	3	0.6	68,74,77,80,86
15	Hilbert transformation	0.72	3	0.6	69,75,78,81,87
16	Differentiation	1.1	6	0.4	70,76,82,88,94
17	Integration	1	1	5	89,90,91,92,93
18	Bandpass Hilbert transformation	1	5.5	0.4	50,61,72,83
19	Differentiation	1.0	11	0.15	51,62,84,95
20	Differentiation	0.05	9	0.2	1,10,19,28,37
21	Differentiation	0.15	9	0.2	2,11,20,29,38
22	Differentiation	0.25	9	0.2	3,12,21,30,39
23	Differentiation	0.35	9	0.2	4,13,22,31,40
24	Differentiation	0.45	9	0.2	5,14,23,32,41
25	Differentiation	0.55	9	0.2	6,15,24,33,42
26	Differentiation	0.65	9	0.2	7,16,25,34,43
27	Differentiation	0.75	9	0.2	8,17,26,35,44
28	Differentiation	0.85	9	0.2	9,18,27,36,45
29	Hilbert transformation	0.97	3	0.6	46,52,55,58,64
30	Hilbert transformation	0.92	3	0.6	47,53,56,59,65
31	Hilbert transformation	0.86	3	0.6	48,54,57,60,66
32	Hilbert transformation	0.81	3	0.6	68,74,77,80,86
33	Hilbert transformation	0.75	3	0.6	69,75,78,81,87
34	Differentiation	0.95	6	0.4	70,76,82,88,94

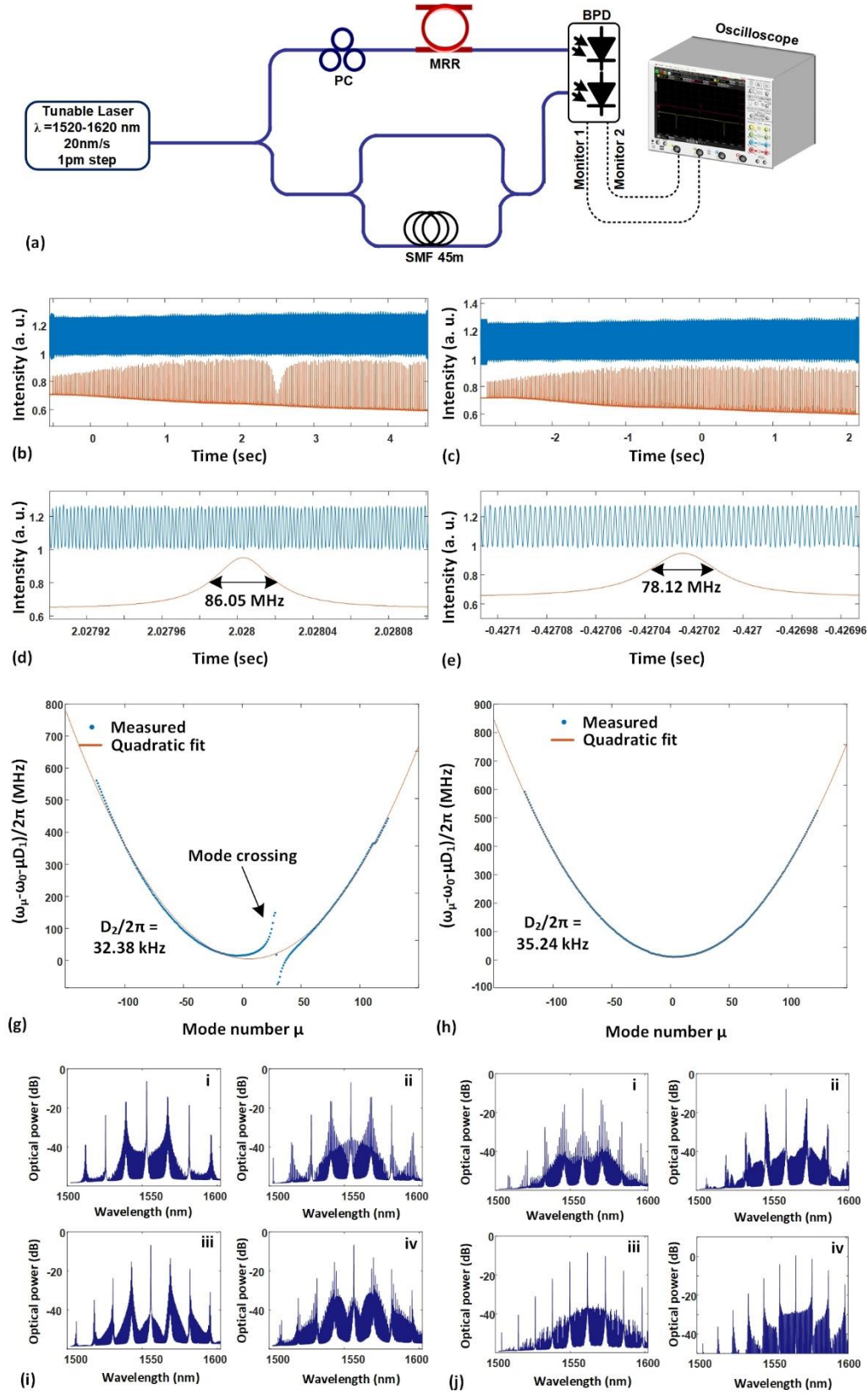


Figure S1. Experimental measurement of the MRR characteristics. PC: polarization controller. BPD: balanced photodetector. (a) Experimental setup. The tunable laser is swept from 1520 to 1620 nm with a speed of 20 nm/s in the measurements. SMF: single mode fibre with a length of 45 m. The transmission traces of TE mode and TM mode are measured respectively by carefully tuning the PC. (b) and (c) The transmission traces of the TE and TM modes together with the fibre

ring resonator transmission traces. (d) and (e) The FWHMs of the two vertically polarized modes are 86.05 MHz and 78.12 MHz, corresponding to Q factors of 2.2×10^6 and 2.4×10^6 respectively. (g) and (h) The calculated and measured dispersion curves of TE and TM modes. (i) and (j) The generated soliton crystal micro-combs of TE and TM modes, respectively.

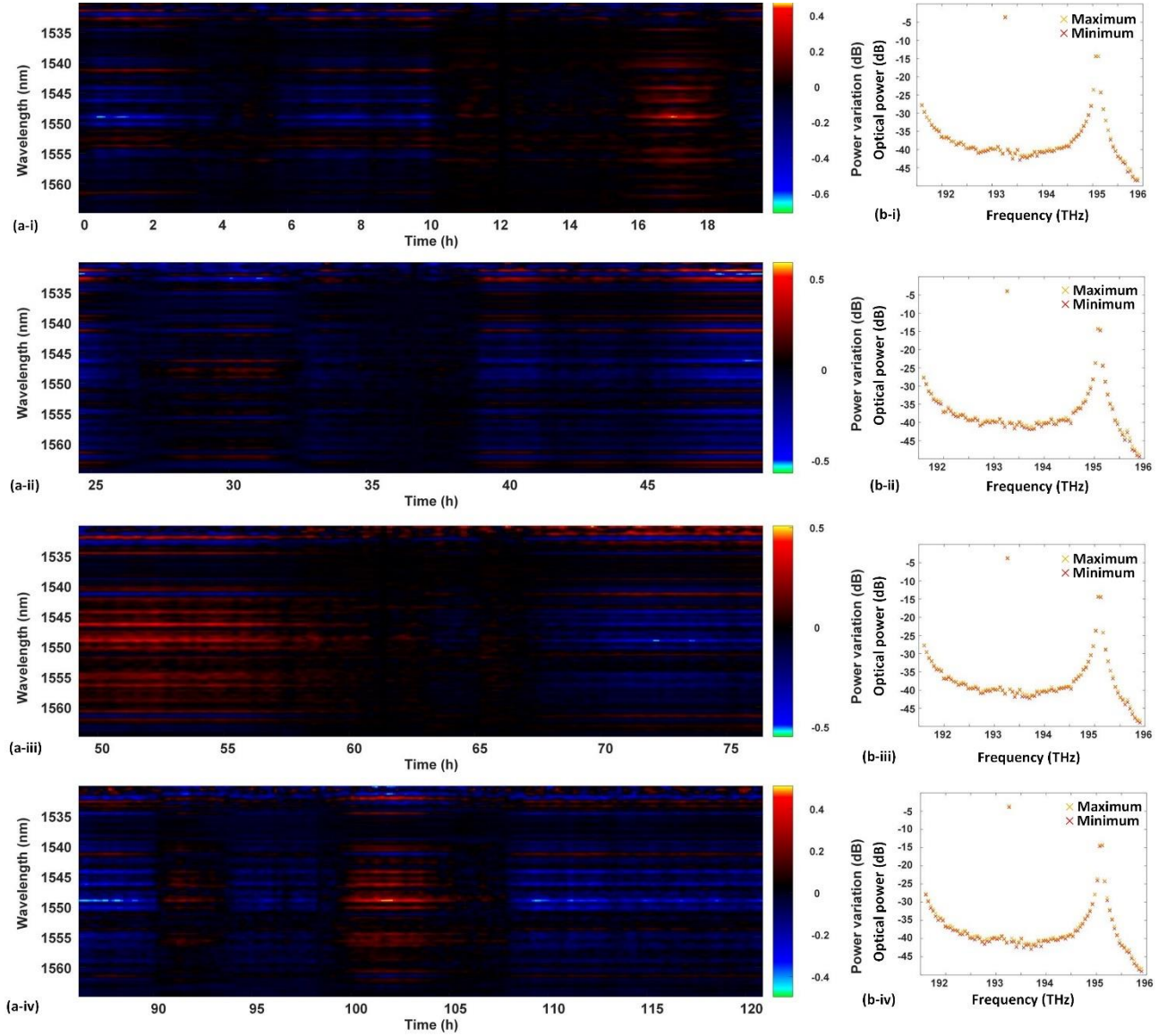


Figure S2. (a) Measured comb power stability over 120 hours (5 days) and extracted (b) deviation between the maximum and minimum optical power.

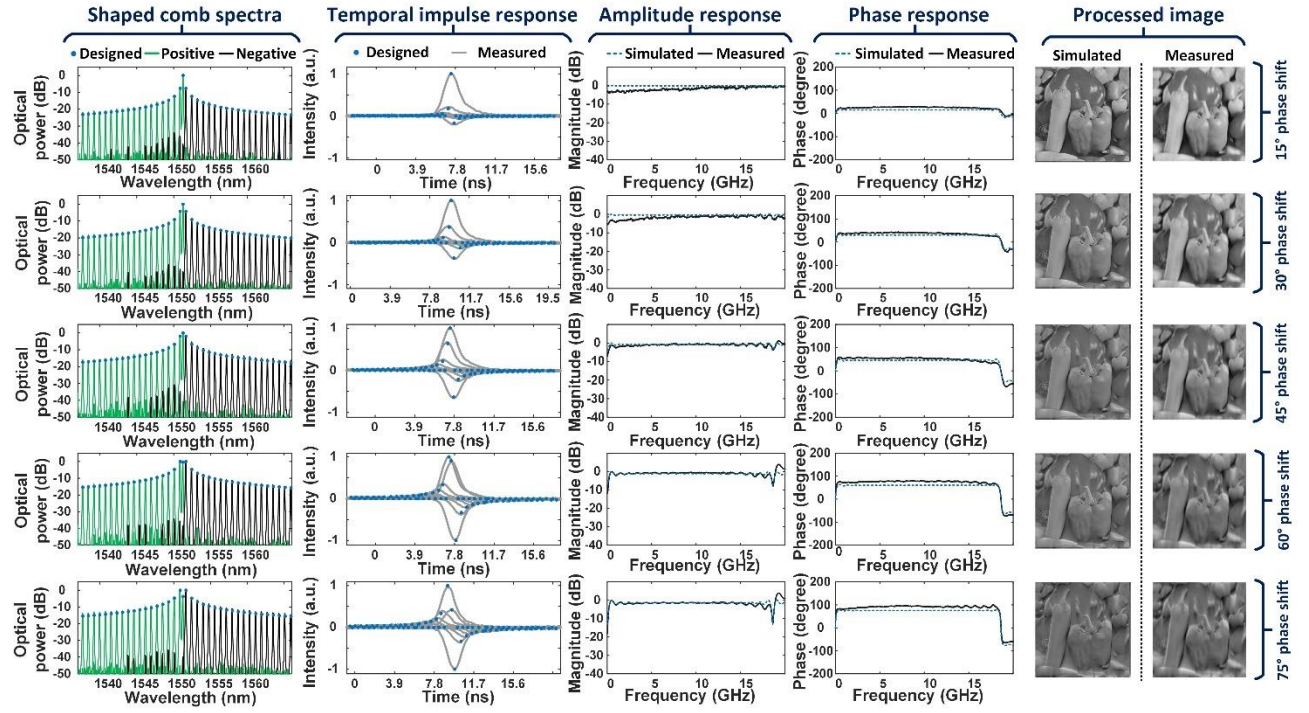


Figure S3. Simulated and measured shaped comb spectra, temporal impulse response, frequency response and processed image of fractional Hilbert transformer with tunable phase shift from 15° to 75°.

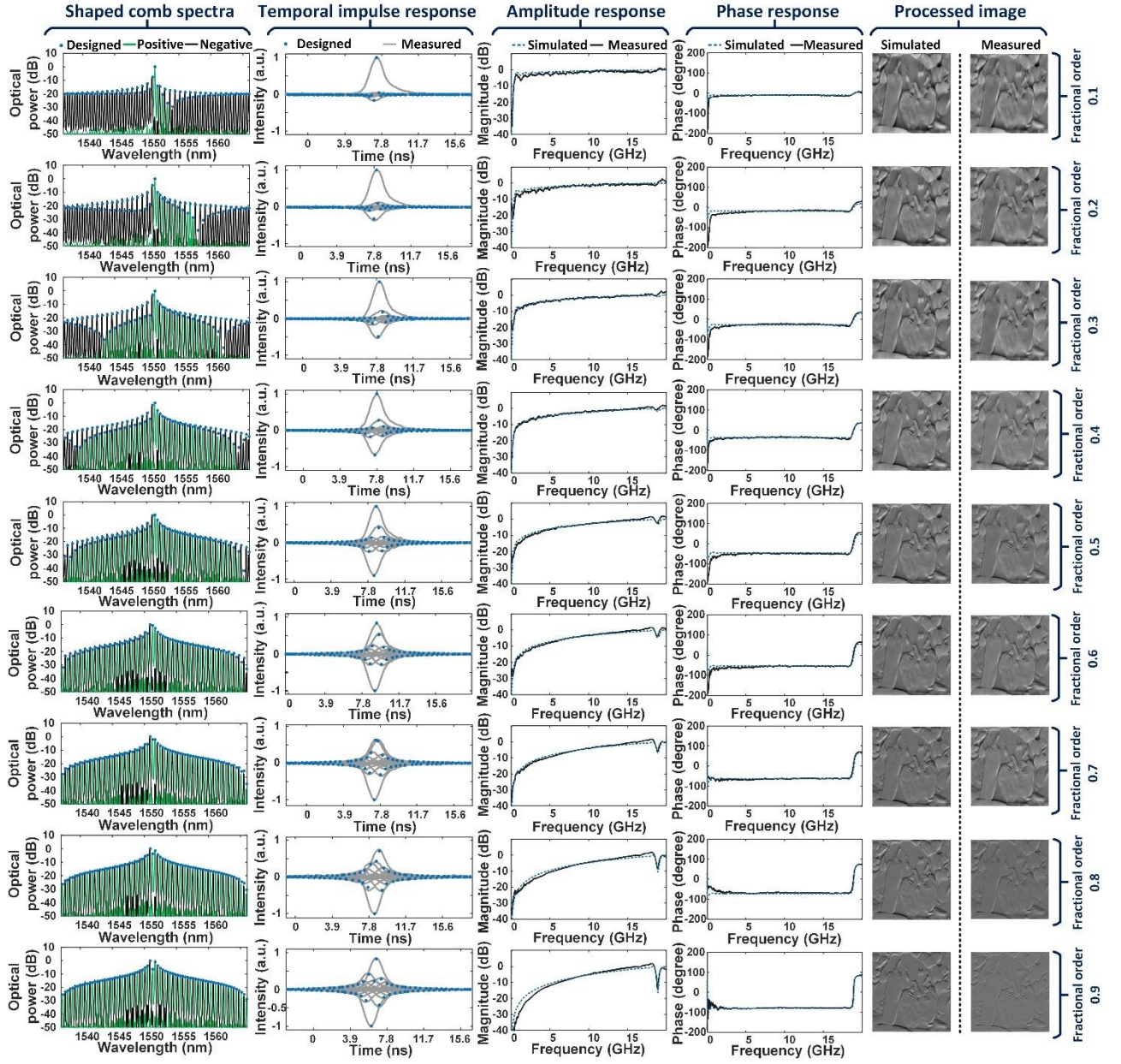


Figure S4. Simulated and measured shaped comb spectra, temporal impulse response, frequency response and processed image of fractional differentiator with tunable order from 0.1 to 0.9.

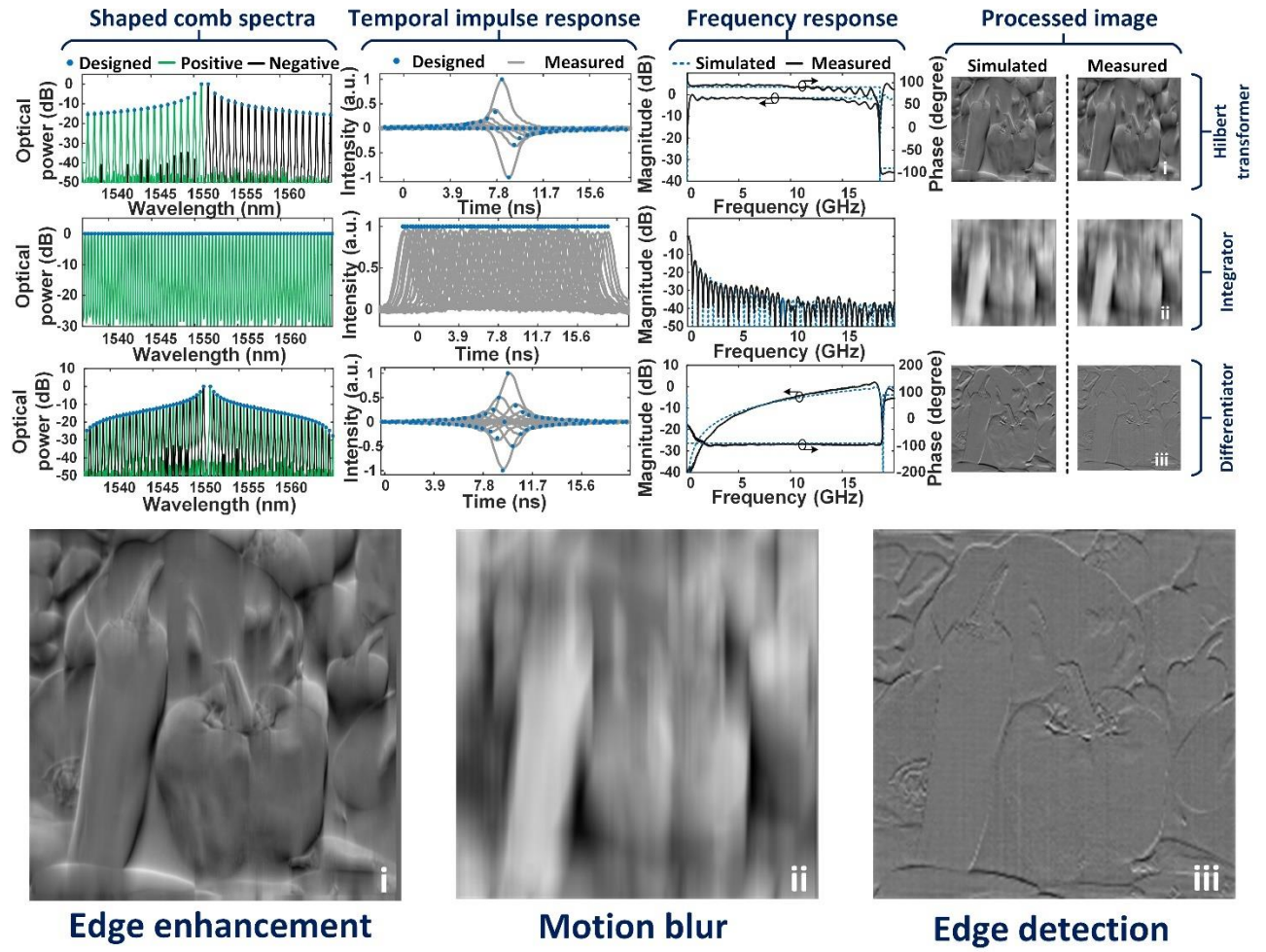


Figure S5. Simulated and measured shaped comb spectra, temporal impulse response, frequency response and processed image of integral signal processor include Hilbert transformer for (i) Edge enhancement, integrator for (ii) Motion blur, and differentiator for (iii) Edge detection.

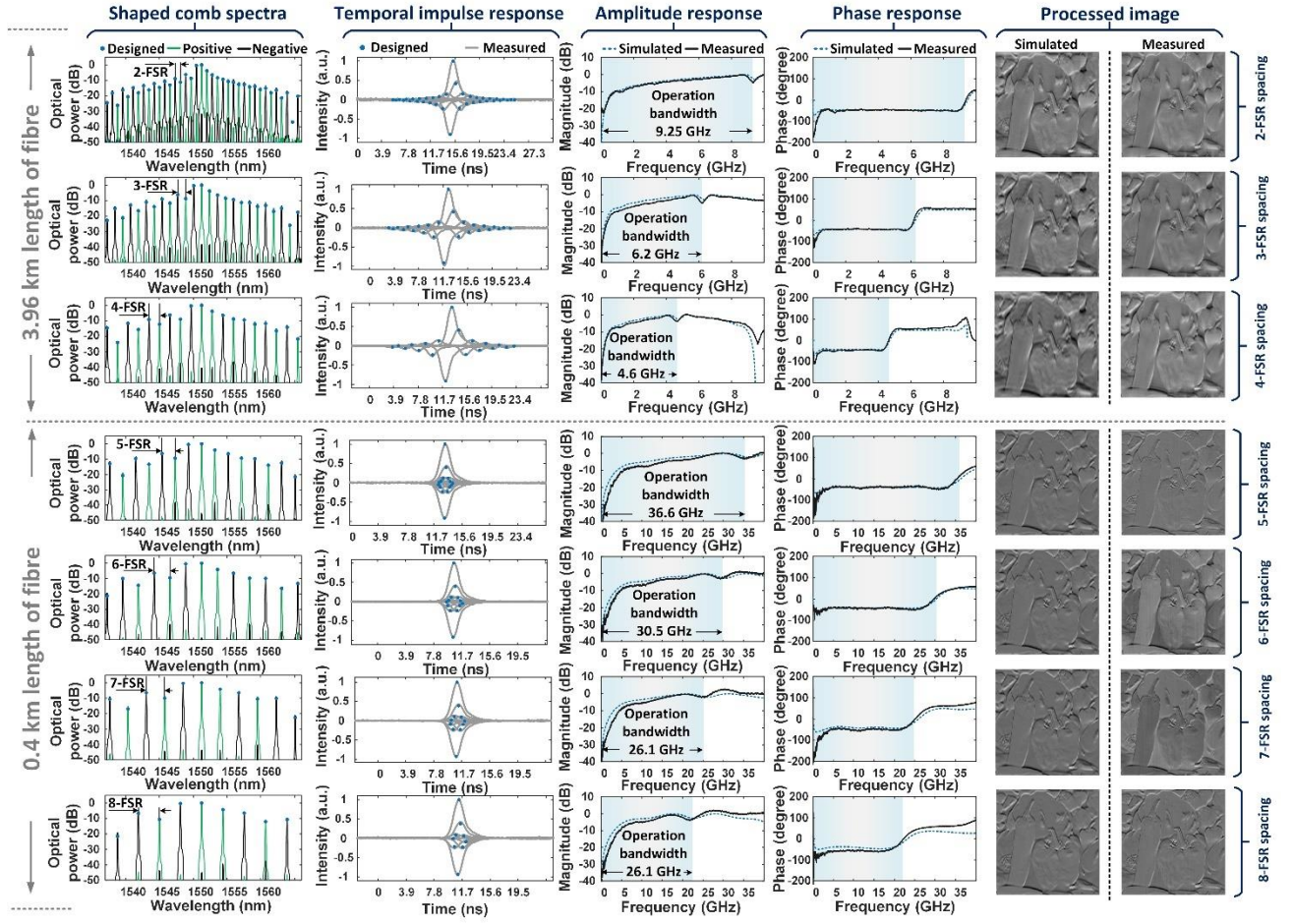


Figure S6. Simulated and measured shaped comb spectra, temporal impulse response, frequency response and processed image of 0.5 order fractional differentiator with varying comb spacing from 2-FSR spacing to 8-FSR spacing and with 0.4 km vs 3.96 km length of fibre.

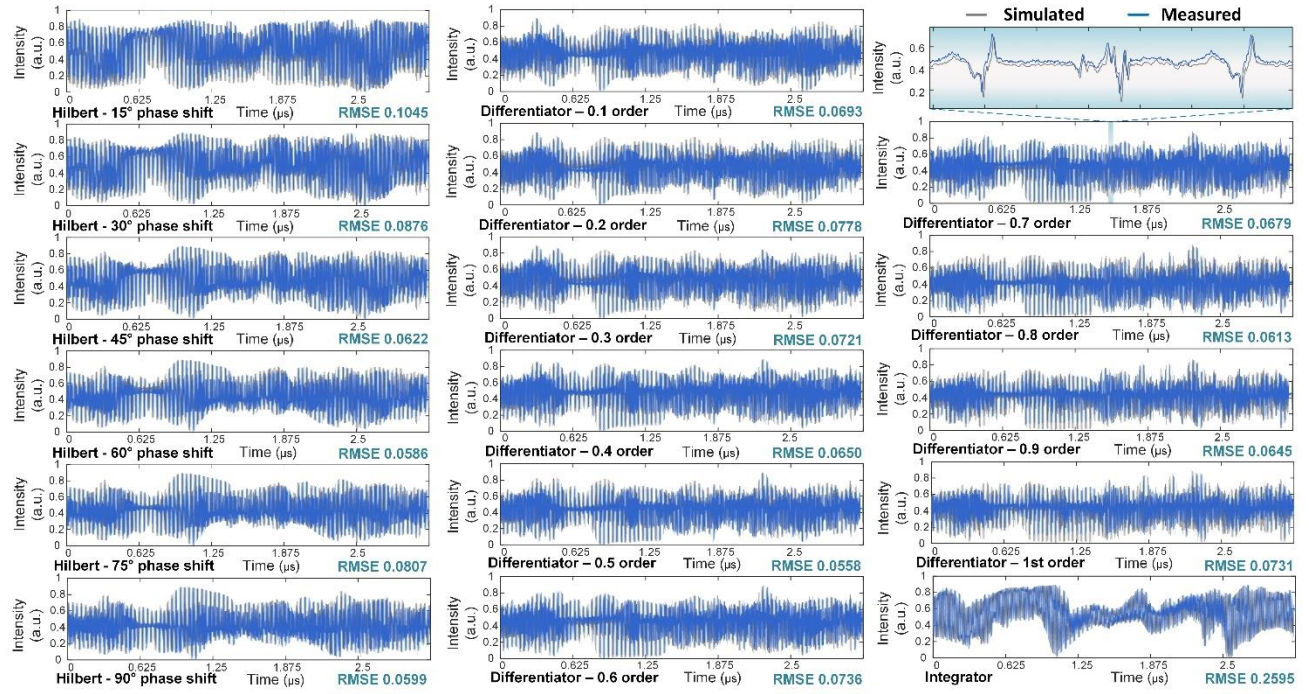


Figure S7. Simulated and measured processed waveforms as well as calculated RMSE.

Table S2. Performance of achieved analog image processing functions.

	RMSE		RMSE		RMSE
Hilbert – 15° phase shift	0.1045	Differentiator – 0.1 order	0.0693	Differentiator – 0.7 order	0.0676
Hilbert – 30° phase shift	0.0876	Differentiator – 0.2 order	0.0778	Differentiator – 0.8 order	0.0613
Hilbert – 45° phase shift	0.0622	Differentiator – 0.3 order	0.0721	Differentiator – 0.9 order	0.0645
Hilbert – 60° phase shift	0.0586	Differentiator – 0.4 order	0.0650	Differentiator – 1.0 order	0.0731
Hilbert – 75° phase shift	0.0807	Differentiator – 0.5 order	0.0558	Integrator	0.2595
Hilbert – 90° phase shift	0.0599	Differentiator – 0.6 order	0.0736		

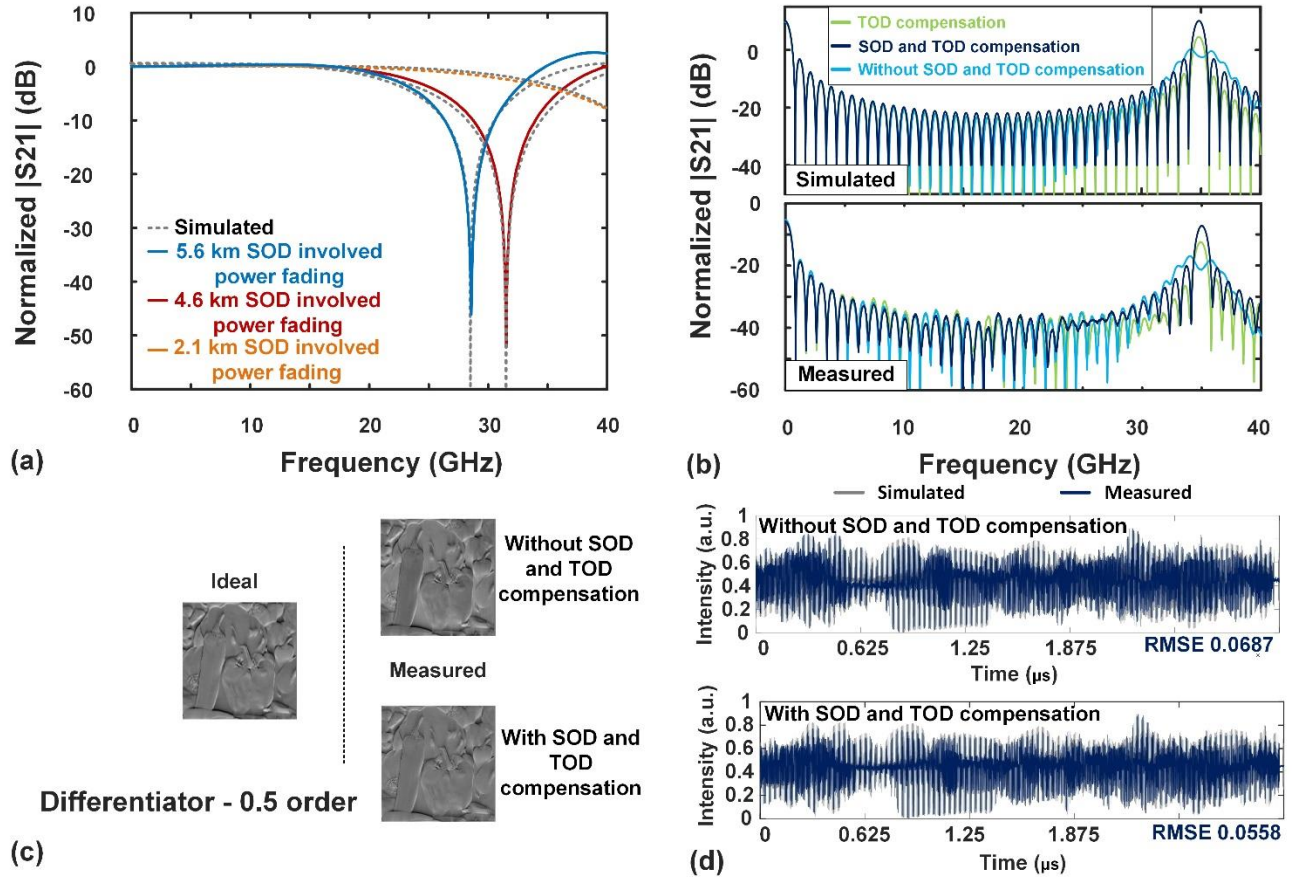


Figure S8. Simulated and measured (a) SOD involved power fading and (b) TOD involved distortion and an integrator with dispersion compensation method achieved. (c) processed image of 0.5 order fractional differentiator with and without SOD and TOD compensation method involved. (d) temporal results of 0.5 order fractional differentiator with and without SOD and TOD compensation method involved and RMSE of the results.

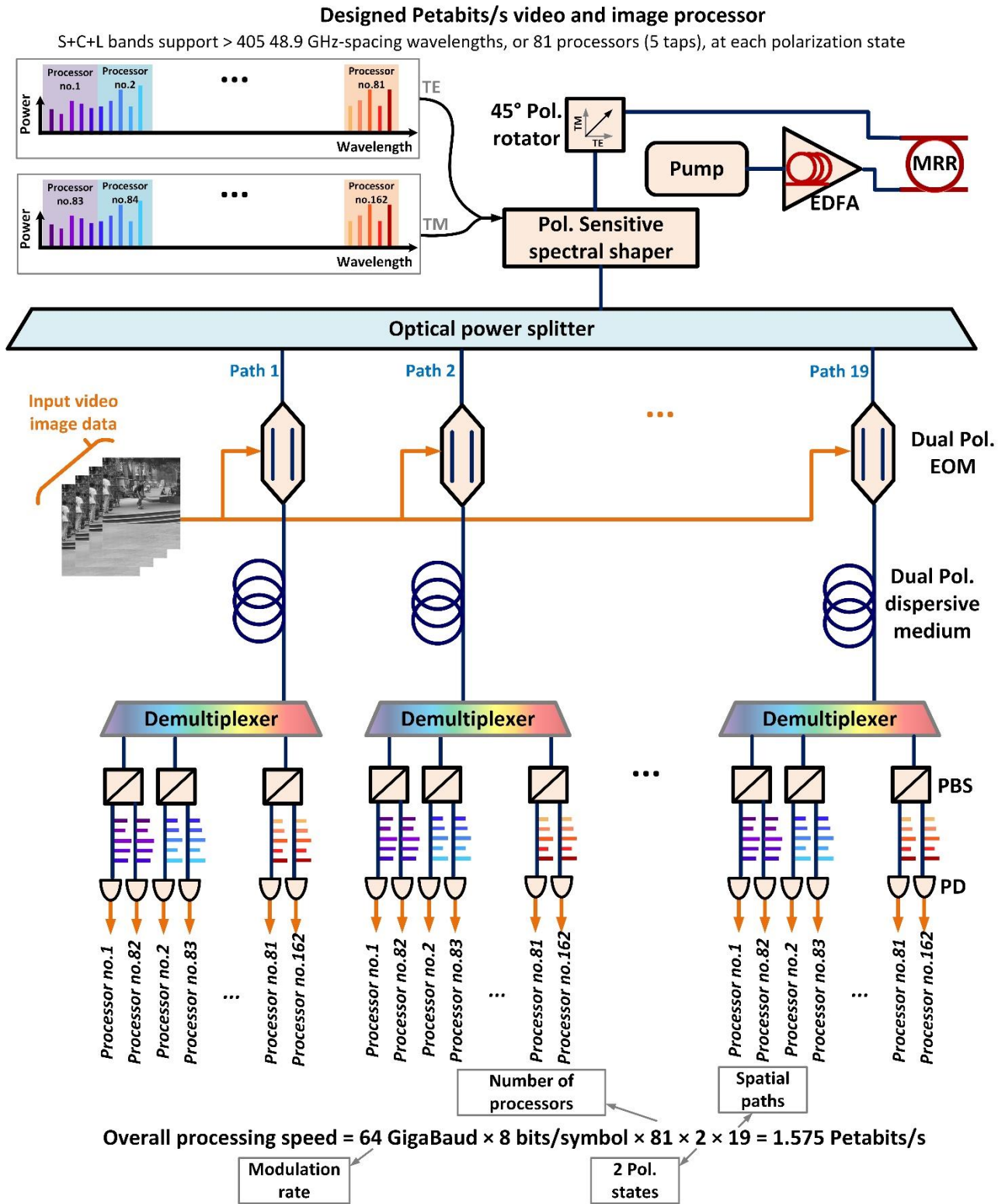


Figure S9. Designed scaled video image processor over the C + L + S bands, with spatial and polarization multiplexing. The 405 available wavelengths (on a 48.9 G grid) would be split into 81 processors each have 5 taps in size. Pump: continuous-wave pump laser. EDFA: erbium doped fibre amplifier. MRR: micro-ring resonator. EOM: electro-optical Mach-Zehnder modulator. PBS: polarization beam splitter. PD: photodetector.