Three dimensional waveguide interconnects for scalable integration of photonic neural networks: supplementary material

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This document provides supplementary information to “Three-dimensional waveguide interconnects for scalable integration of photonic neural networks,” https://doi.org/10.1364/OPTICA.388205. In this supplementary material, we first discuss the design specifics of the chiral fractal trees and afterward we describe the optical characterization setup in detail.

1. CHIRAL FRACTAL TREES

The branching concept introduced in the main article leverages a fractal, i.e. scale-free approach to link an input channel to a large number of outputs. The number of established connections exponentially grows with the number of bifurcations, and hence this concept efficiently establishes networks with a high degree of connectivity. However, the full interconnect between many IO-channels requires a dedicated coupler for each input channel. As soon as fractal trees of neighboring input channels occupy the same volume, their connections start to intersect, see Fig. S1. The top and bottom rows correspond to projections onto the (x,y) or (x,z) plane, respectively. In each square we introduce the individual units of a 1 × 9 splitter, plus their arrangement in a 2 × 2 lattice. The 2 × 2 arrangement is the smallest network motif where all potential connections, i.e. intersections, are found in the space between the units.

Intersections pose two major challenges. First, they will result in significant crosstalk and additional losses. Second, 3D couplers can at some future stage be amended with phase-shifting elements. This would potentially enable programmable and unitary mapping from the input to the output waveguides, comparable to the 2D Mach-Zehnder meshes \cite{1}. Waveguides intersecting at positions where no interference is desired will almost certainly impede control and programmability.

Figure S1(a) illustrates the situation for simply creating a net-
work of 3D fractal couplers with straight connections. The mirror symmetry between neighboring units results in numerous intersecting connections in the space between different couplers (indicated by different colors). Projected onto the (x,y)-plane, waveguides can intersect along (i) horizontal connections: be-

Between the input of a fractal branching and its output \( i \), we have \( \Delta x_i = x_i^O - x^i, \Delta y_i = y_i^O - y^i \) and \( \Delta z_i = z_i^O - z^i \) as the distances in \( x \), \( y \) and \( z \), respectively. Superscripts \( \{I,O\} \) assign a position to the input and output, respectively. We curve waveguides in the (x,y) plane according to

\[
x_i^c(z) = \Delta x_i \sin \left( \frac{\pi}{i} x_i(z) \right)^2
\]

\[
y_i^c(z) = \Delta y_i \sin \left( \frac{\pi}{i} y_i(z) \right)^2,
\]

and the resulting structure using \( x(z) = x_i^I + x_i^c(z) \) and \( y(z) = y_i^I + y_i^c(z) \) is schematically illustrated in Fig. S1(b). Chirality in the (x,y) plane successfully avoids intersections between horizontal and vertical connections.

However, diagonal connections between neighboring trees still appear, though their degeneracy has been reduced: at each point we now simply find two links intersecting. We therefore include chirality also along the z-direction by an additional displacement in \( x \) and \( y \)

\[
x_i^{d_{x}}(z) = w \Delta y_i \sin \left( \frac{\pi}{i} \sqrt{\frac{x_i^c(z)^2 + y_i^c(z)^2}{\Delta x_i^2 + \Delta y_i^2}} \right)
\]

\[
y_i^{d_{y}}(z) = -w \Delta x_i \sin \left( \frac{\pi}{i} \sqrt{\frac{x_i^c(z)^2 + y_i^c(z)^2}{\Delta x_i^2 + \Delta y_i^2}} \right),
\]

where \( w \) is the offset, see Fig. S1(c). Using \( x(z) = x_i^I + x_i^c(z) + x_i^{d_{x}}(z) \) and \( y(z) = y_i^I + y_i^c(z) + y_i^{d_{y}}(z) \) is schematically illustrated in Fig. S1(c). Here we have used different shading of colors to indicate different positions along the \( y \) direction. All crossings are removed, and due to the scale-free nature this approach should be applicable to larger numbers of bifurcation layers.

2. OPTICAL CHARACTERIZATION

We have characterized the optical transmission of the 3D-printed polymer waveguides with the experimental setup depicted in Fig. S2. Only optical components are illustrated in this setup. The emission of a semiconductor laser emitting at 635 nm is col-

\[
\begin{align*}
LD & \quad \text{CAM}_R \\
\text{Sample} & \quad \text{LED} \\
\text{CAM}_T
\end{align*}
\]

Fig. S2. Experimental setup for optical characterization of the 3D printed waveguides. The laser diode (LD) emission was focused onto the top facets of the waveguides by a 50x microscope objective. An LED centered at 635 nm was used as broad field illumination for coarse positioning of the sample. Two CMOS cameras respectively imaged the reflection from the top facet of the waveguides (CAM\(_R\)) and the transmission through the bottom of the waveguides (CAM\(_T\)).

REFERENCES

1. D. A. B. Miller, “Perfect optics with imperfect components,” Optica 2, 747 (2015).