Supplementary Material

# Meta-atoms Library

We set up a meta-atoms library composed of multiple germanium nanopillars. When light travels through a nanostructure, a portion of the light is confined inside the nanostructure, while the rest leaks into the surrounding material. This is similar to what occurs in a waveguide. Owing to this similarity, the optical properties of nanostructures can be better understood by treating them as miniature truncated waveguides. As illustrated in Supplementary Figure 1, three meta-atom archetypes are employed in our library: one nanofin corresponds to a rectangular miniature waveguide, two nanofins correspond to slotted miniature waveguides, and three nanofins correspond to multislotted miniature waveguides. Supplementary Figures 1 A to C show the conversion efficiency and phase spectra for the three selected meta-atoms. The phases of the three meta-atoms were linear with respect to the frequency within the operating bandwidth, and the group delays of the three meta-atoms were 0.82 ps, 1.13 ps, and 0.67 ps, respectively. Supplementary Figure 1D shows the top and side views of the normalized magnetic energy density in a periodic array for the three selected nanostructures. Owing to the waveguide-like effect, the light was observed to mostly remain within the nanostructures. This indicates that the group delay design for the elements was accurate even when arranged in a square lattice as a metasurface array; thus, the light coupling effects between adjacent pairs of elements can be ignored.



**Supplementary Figure 1.** Simulation results for three selected meta-atoms. (**A**) Phase and conversion efficiency spectrum for one nanofin, geometry parameters in the inset picture: L1 = 4.4 μm, W1 = 2.2 μm; (**B**) Phase and conversion efficiency spectrum for two nanofins, geometry parameters in the inset picture: L1 = 4.3 μm, W1 = 1.3 μm, g1 = 0.5 μm, L2 = 1.9 μm, W2 = 1.9 μm; (**C**) Phase and conversion efficiency spectrum for three nanofins, geometry parameters in the inset picture: L1 = 1.3 μm, W1 = 1 μm, g1 = 0.5 μm, L2 = 2.1 μm, W2 = 1 μm, L3 = 1.1 μm, W3 = 1 μm; (**D**) top and side views of normalized H field intensities for the three meta-atoms.

# Metasurface generating optical vortices with and

To confirm the universal nature of our method, we show the metasurfaces to generate optical vortices of different orders. Supplementary Figure 2 and 3 show the simulation results of metasurface generating optical vortices with . Supplementary Figure 4 and 5 show the simulation results of metasurface generating optical vortices with .



**Supplementary Figure 2.** Intensity and phase distribution at the focal plane for metasurface generating OAM with.



**Supplementary Figure 3.** Intensity distribution on XOZ plane for metasurface generating OAM with.



**Supplementary Figure 4.** Intensity and phase distribution at the focal plane for metasurface generating OAM with.



**Supplementary Figure 5.** Intensity distribution on XOZ plane for metasurface generating OAM with.

# Transmittance of the meta-atoms



**Supplementary Figure 6.** Transmittance of the selected meta-atoms shown in Figure 2C.