Supporting Information

Widely Tunable Distributed Bragg Reflectors Integrated into Nanowire Waveguides

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Fabrication Procedure: Single-crystalline GaN nanowires were synthesized using chemical vapor transport on c-plane sapphire substrates coated in 2-10 nm of Ni in a hot-wall furnace. The furnace was held at a temperature of 900-1000 ^{o}C to enable the direct reaction between gallium metal (99.9995% metals; Sigma Aldrich) and NH_3 gas (10-30 sccm) with a small amount of H_2 gas (~1-3 sccm). The as-synthesized GaN nanowires had lengths normally ranging from 20-150-μm long with diameters mostly between 200-300 nm. Using a micromanipulator, single, long GaN nanowires were selectively transferred onto fused silica substrates that were 150-μm thick. About 20-30 nm of tungsten was then deposited onto the samples by sputtering (Edwards Auto 306 DC and RF Sputter Coater) for 30 seconds with the shutter closer closed, followed by 1 minute with the shutter opened at 200 W DC in an Ar environment. A focused ion beam (Zeiss Crossbeam 1540 EsB) was then used to mill partial indentations with controlled periodicities and indentation widths. These parameters were controlled by adjusting the dosage times with the width of the pattern. A single Ga ion image was recorded before milling in order to perform x, y, and θ alignments in order to precisely fabricate grating structures with a total of 50 periods (occasionally 100) onto single nanowires. Occasionally, the focused ion beam was used to mill the end facets as well to obtain symmetric end facets on a nanowire. After milling, the tungsten layer was removed with hydrogen peroxide (30% w/w; Sigma Aldrich) at 80^{o}C for 15-30 seconds and the sample was washed with deionized water. Finally, the sample was annealed in a hot-wall furnace at 700-850^{o}C for 5-30 minutes in a N_2 atmosphere.

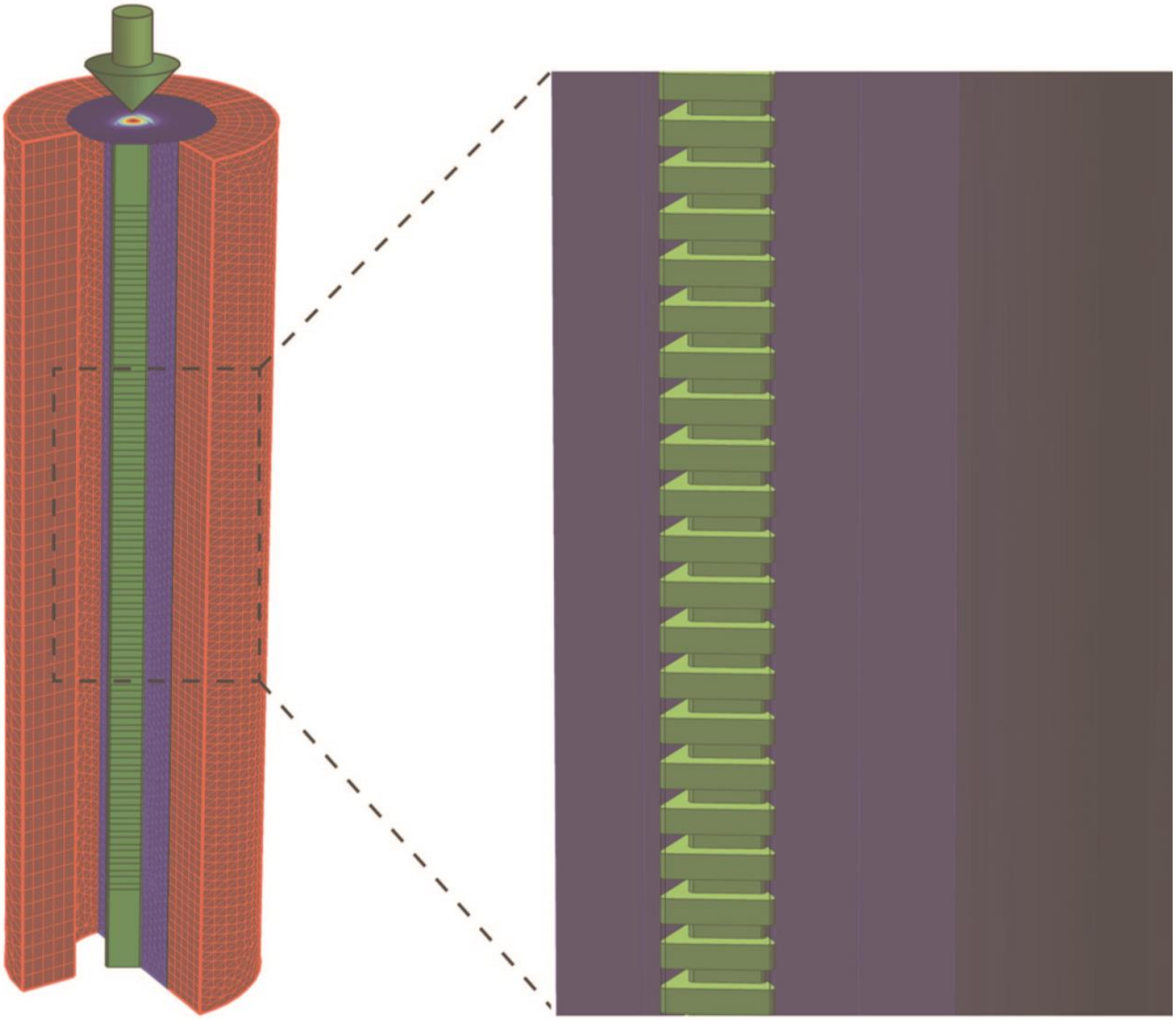

Figure S1. Schematic of the 3D finite-element simulations. The fundamental mode was injected from the top surface and propagated through the nanowire (green). The nanowire is surrounded by a cylindrical region, half fused silica (blue) and half air, and everything is enclosed by a perfectly matched layer that absorbs all scattered electromagnetic waves. The superimposed grid indicates the meshing size used in the simulations. The geometry of the structure is adjusted to each fabricated device. The complex reflection coefficients, transmission coefficients, and optical loss are extracted by monitoring the wave's propagation through the structure.

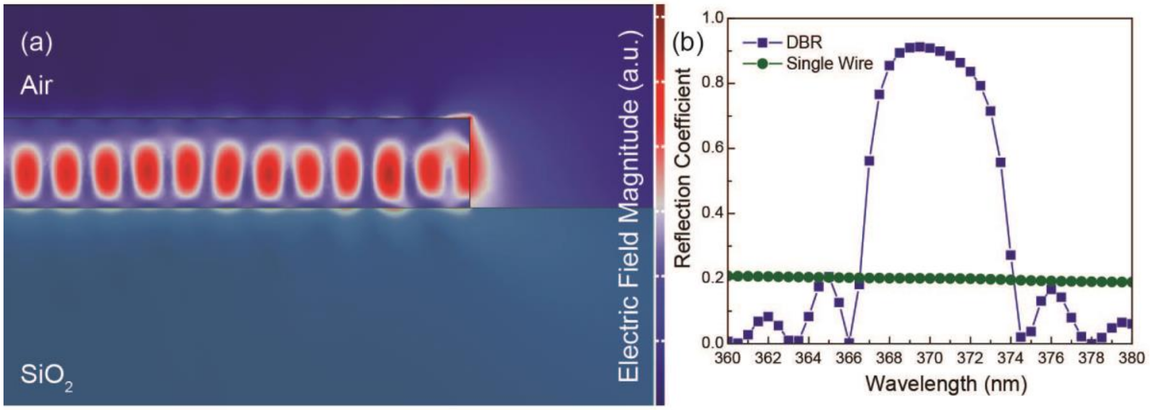

Figure S2. Reflectivity of a single nanowire's end facet. The fundamental mode was injected from the left and propagated through the nanowire. The nanowire is surrounded by a cylindrical region, half fused silica (bottom) and half air (top), and everything is enclosed by a perfectly matched layer that absorbs all scattered electromagnetic waves. (a) Field plot of a single nanowire on top of a fused silica substrate. (b) A plot of the reflection coefficients of a single nanowire and a distributed Bragg reflector (DBR) in a nanowire showing that a DBR can improve the reflectivity from ~20% to ~90%.

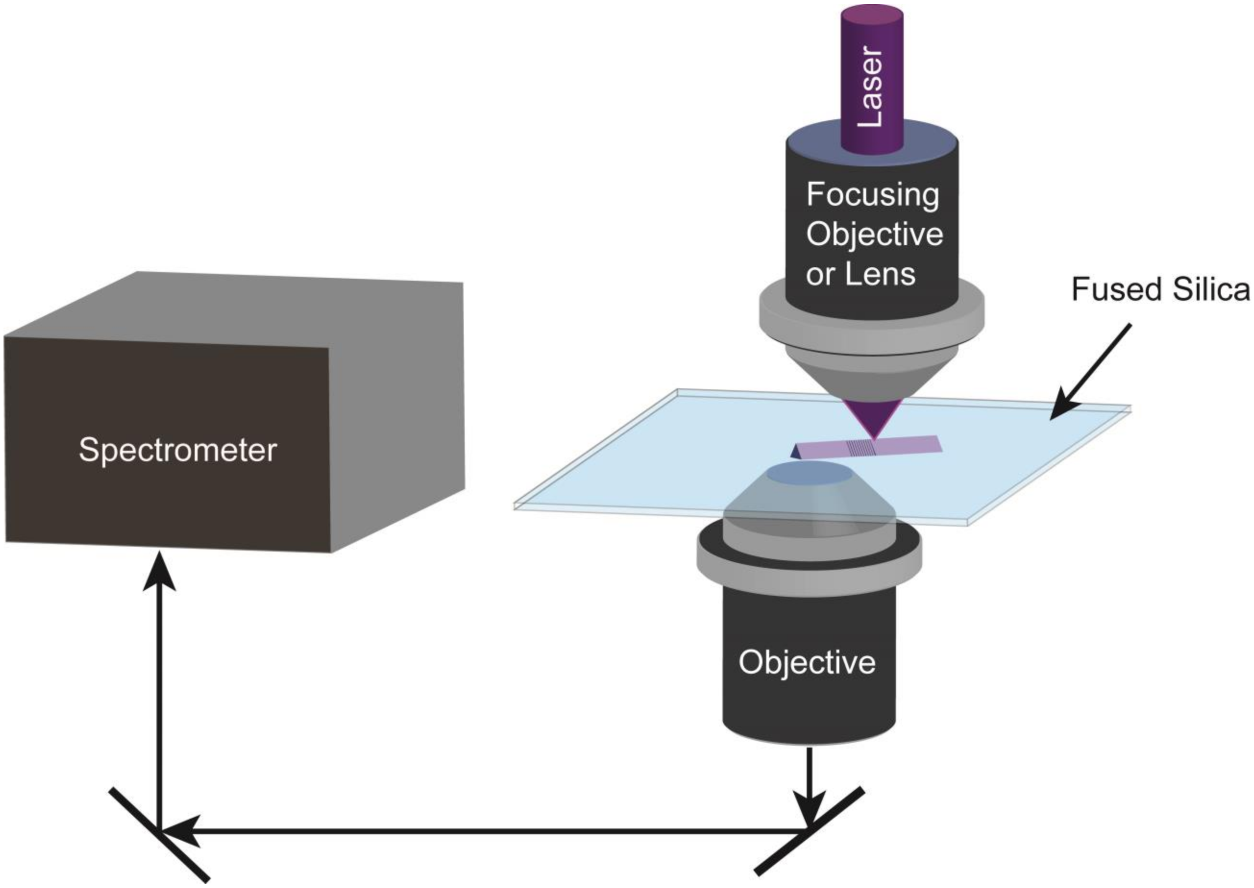

Figure S3. Selected-area spectroscopy measurement. A focusing lens or objective is used to focus a laser onto the center of the device. The image of the nanowire is projected onto the liquid-N_2 cooled CCD of the spectrometer by using the grating as a mirror (centered at 0 nm). The spectrometer is then used to collect the spectrum of a specific area of the image by isolating pixels from the image to be dispersed. In this case, the spectrum of the mode that propagates through the DBR and the spectrum of the mode that doesn't propagate through the DBR are collected and compared to calculate the normalized transmission spectrum.

The sample was placed face down on the stage of an inverted microscope (Olympus microscope) with a 60X microscope objective (Olympus N.A. 0.7) and the image of the fabricated nanowire was projected onto the liquid N_2-cooled charge-coupled device of a UV-visible spectroscopy spectrometer (Princeton Instruments/Acton) equipped with a 300 grooves/mm grating blazed at 500 nm. After imaging the nanowire onto the charge-coupled device, the spectra from selected end facets were collected by the same spectrometer. The 325 nm laser line from a helium-cadmium laser (Melles-Griot) was focused to a spot size of several microns in diameter to excite the center of the nanowire structure. These GaN nanowires exhibit defect emission in the visible; it is this emission that is used to measure the stop band. By exciting the center of the structure, the nominal propagation loss through the nanowire waveguide is normalized out in the comparison of the spectra. The measured spectra also occasionally display multiple peaks around the stop band. These peaks correspond to the Fabry–Pérot resonances associated with the nanowire cavity structure on the shorter nanowires (<40-μm long) and the fabricated grating structure and are more pronounced at longer wavelengths, as expected. The spontaneous defect emission creates a relatively large background in our signal. This large background makes it more difficult to elucidate a reflection spectrum. While a spike in the spectrum collected from the DBR-free end of a wire is observed, it is difficult to extract quantitative information from it. It is easier to elucidate the effect of the DBR from the transmission spectrum because it is not convoluted with the loss. We believe that the tunable transmission spectrum is sufficient evidence to suggest that we can controllably tune a DBR that is directly integrated into a nanowire.

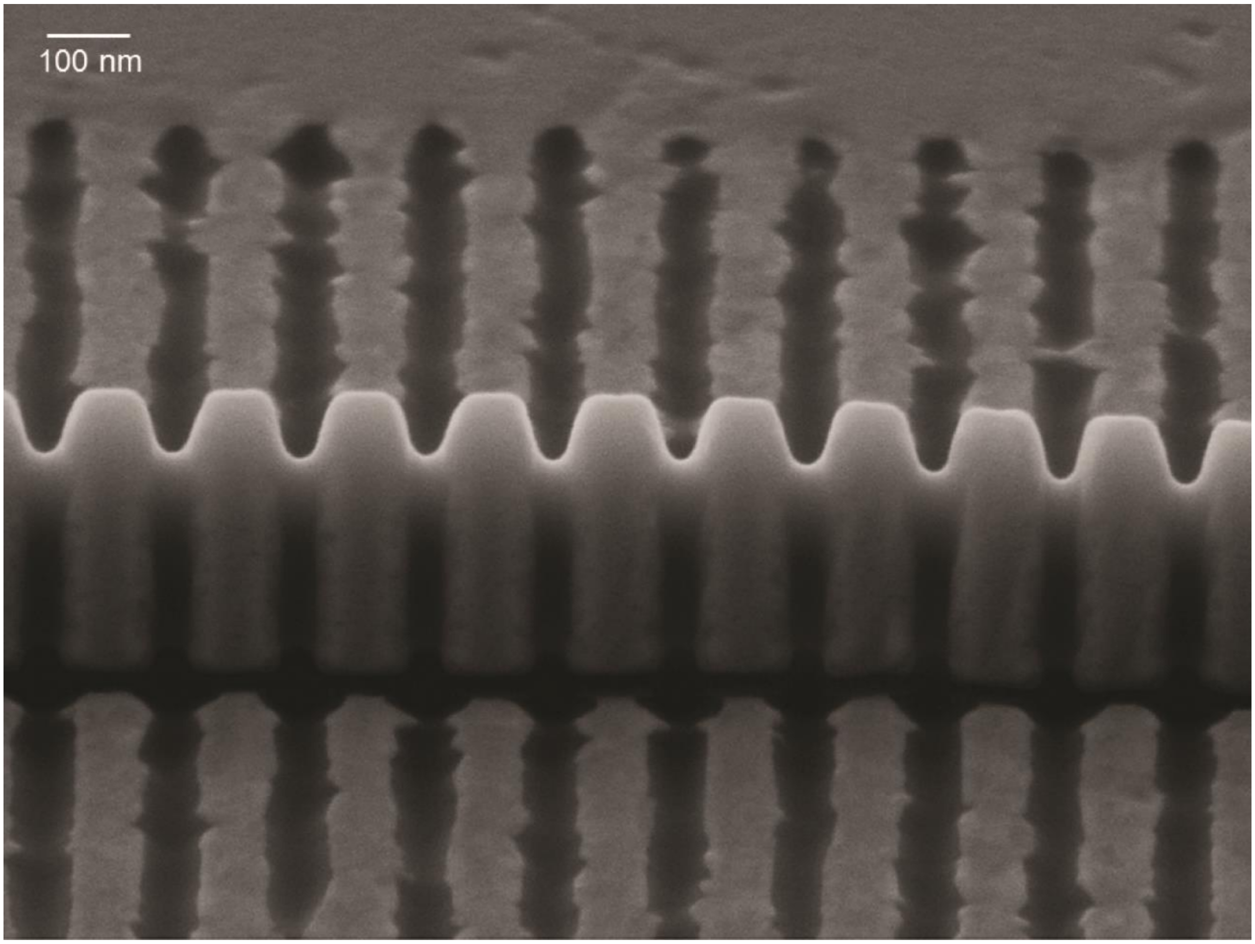

Figure S4. Scanning electron microscopy (SEM) image of a gallium nitride nanowire with a tungsten metal coating after focused ion beam milling showing uniform cuts.

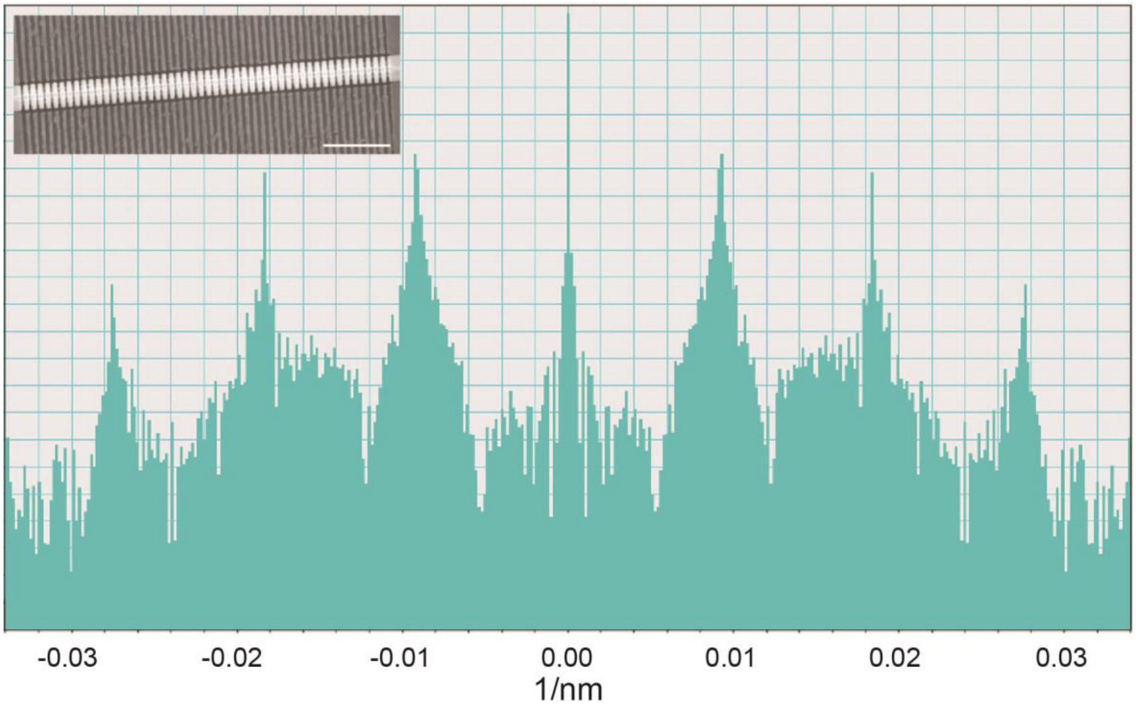

Figure S5. Fast Fourier transform of a line scan of a top-down SEM image of a DBR structure in a single gallium nitride nanowire. This analysis gives a periodicity of 107-110 nm, which is the largest source of error in calculating the index of refraction. Scale bar = 1 μm.

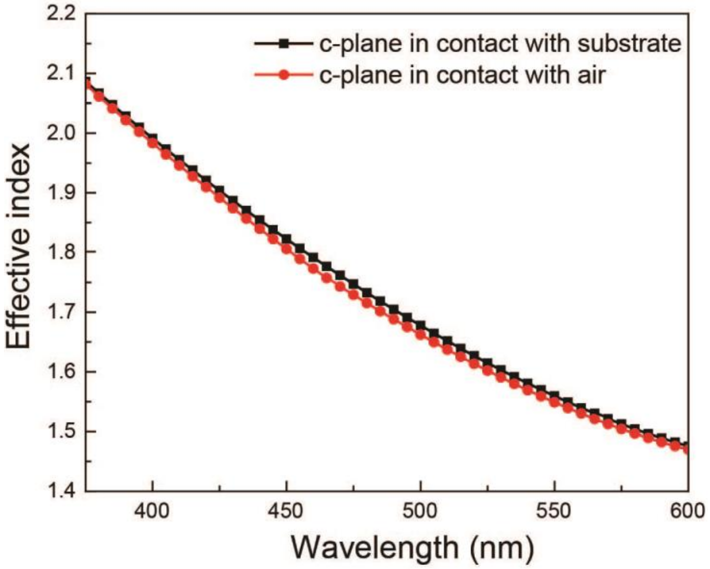

Figure S6. Simulation of the effective index of a triangular gallium nitride nanowire waveguide. The difference in the two curves shows the effect of the nanowire's orientation on the substrate. In black, the c-plane facet is in contact with the substrate, and in red, the nanowire is rotated with the c-plane facet in contact with air. The difference is smaller than the error in the measurement.