NANO LETTERS

2004
Vol. 4, No. 10
1981−1985

Nanowire Photonic Circuit Elements

Carl J. Barrelet,[†,§] Andrew B. Greytak,[†,§] and Charles M. Lieber*,[†,‡]

Department of Chemistry and Chemical Biology and Division of Engineering and Applied Sciences, Harvard University, Cambridge, Massachusetts 02138

Received August 3, 2004; Revised Manuscript Received August 19, 2004

ABSTRACT

We report an approach for guiding and manipulating light on sub-wavelength scales using active nanowire waveguides and devices. Quantitative studies of cadmium sulfide (CdS) nanowire structures show that light propagation takes place with only moderate losses through sharp and even acute angle bends. In addition, measurements demonstrate that efficient injection into and modulation of light through nanowire waveguides are achievable in active devices. The ability to inject, guide, and manipulate light on a sub-wavelength scale using nanowire components that can be assembled into integrated structures represents a promising pathway towards integrated nanoscale photonic systems.

Integrated photonics have the potential to overcome limitations of speed and power dissipation being faced in silicon-based electronics, and thereby enable applications from advanced communications to revolutionary computing systems.[1−3] Central to progress in this area has been the development of materials and structures, including photonic crystals (PCs)[4,5] and plasmon waveguides,[3,6] that can guide and manipulate light in increasingly complex ways. Precisely defined defects can produce waveguides in PCs that enable light to be guided through sharp bends,[2,7] although the length scale of these structures is still on the order of the wavelength of light. Light has been transported in much smaller structures using nanoscale plasmon waveguides consisting of metal nanoparticles;[3,6,8] however, these have shown substantial losses. Submicron wires or nanowires can also function as waveguides,[9−12] yet work[12] suggests that bends will require curvatures larger than PC- and plasmon-based approaches due to the exponential dependence of loss (attenuation coefficient) on the radius of curvature in dielectric waveguide bends.[13] Resonant structures[14] and integrated mirrors[15] can improve the transmission at sharp bends in dielectric waveguides, but it remains unclear whether passive waveguides[1,3] could be used to manipulate light as required for integrated photonics.

Straight semiconducting nanowires can function as nanoscale lasers,[9,11] where the high refractive index contrast between the nanowire and surroundings defines a sub-wavelength diameter optical cavity. These cavities also function as waveguides, although losses, which are critical measures of the guiding efficiency, have not been characterized in previous studies. In addition, these semiconducting nanowire structures are distinct from conventional transparent dielectric waveguides[1] since absorption and emission occur for modes with near band edge energies. We thus term the semiconducting nanowires as "active waveguides" when operated near band-edge, by analogy to their active medium function in nanolasers.

To evaluate the potential of active nanowire waveguides, we have quantitatively characterized losses through straight and sharply bent sub-wavelength diameter CdS nanowire[16−19] structures using scanning optical microscopy (SOM). In these experiments,[20] spatial maps of the intensity of light emitted from the end of a nanowire (Figure 1A) are recorded as a function of the position of a diffraction-limited laser spot that is higher in energy than the band gap of CdS (see also, Figure S1, Supporting Information). The raw data are reported without making assumptions about reflections at the ends and bends. The laser energy is absorbed by the CdS nanowire and a portion of the resulting photoluminescence (PL) light is guided by the nanowire. A SOM image recorded from a nearly straight, 50 μm long nanowire (Figure 1B) exhibits little intensity variation as a function of detector-laser excitation source separation along the wire, which is indicative of a good waveguide. A plot of intensity vs position quantitatively shows that there is no loss[21] in this nanowire within the limits of our measurement. These data demonstrate that waveguiding can be very efficient in a straight nanowire structure, although surface defects can lead to losses.

Central to the present studies is the characterization of waveguiding through sharp bends in CdS nanowire structures. A SOM image recorded from a CdS nanowire with a bend formed by a change in axial growth direction (Figure 1C) shows that the optical loss is small across this sharp bend; the bend angle, which is defined as the deviation from propagation along a straight path, was 59 ± 1°. The radius of curvature for such abrupt bends is not well-defined,

* Corresponding author. E-mail: cml@cmliris.harvard.edu.
[†] Department of Chemistry and Chemical Biology.
[‡] Division of Engineering and Applied Sciences.
[§] These authors contributed equally to this work.

10.1021/nl048739k CCC: $27.50
Published on Web 09/14/2004

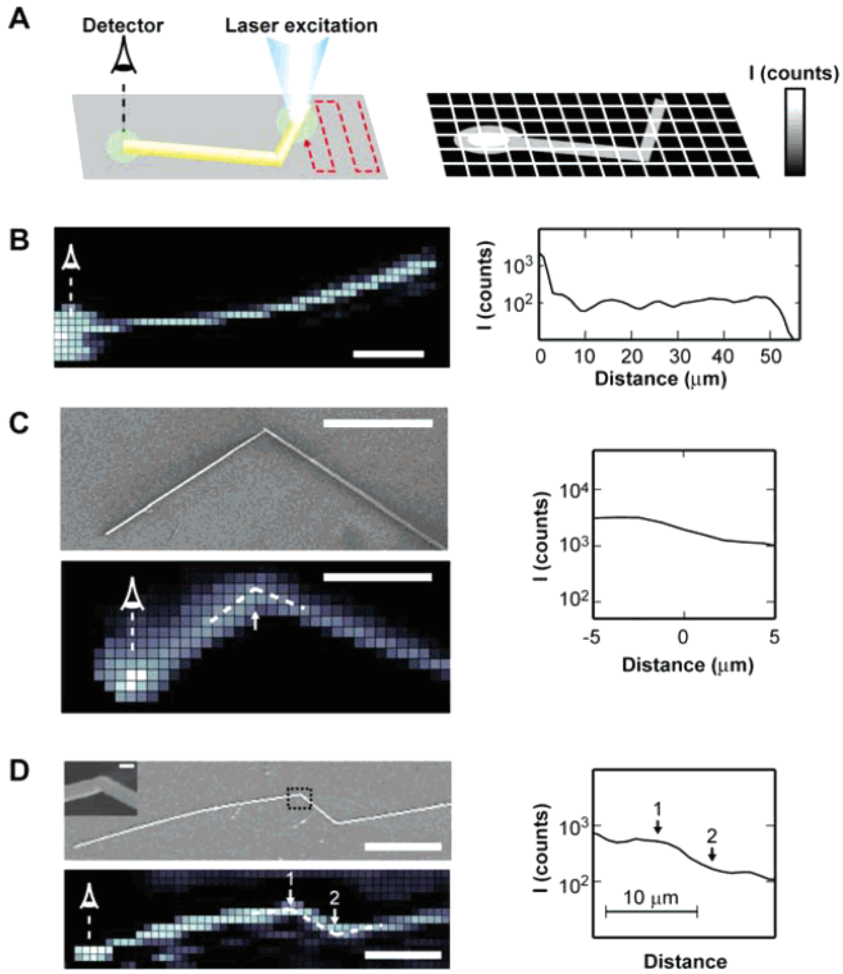

Figure 1. Characterization of optical waveguiding in straight and bent nanowires. (A) Scheme for SOM illustrating focused laser spot scanned over the sample while monitoring light emission from one end of the nanowire. The intensity at the end indicated by the detector is plotted on a color scale as a function of laser position to generate SOM images. (B) At left, SOM image of a single CdS nanowire; the reference end is indicated with detector. Lighter colors correspond to greater end intensity. The scale bar is 10 μm. At right, dependence of the end intensity on the distance between the laser spot and the end of the wire for a path that follows the wire. (C) Upper left, scanning electron micrograph (SEM) of the nanowire structure. Lower left, corresponding SOM image. The scale bars in both images are 10 μm. At right, intensity profile along the path indicated in the SOM image, with the location of the bend (designated by the white arrow) set as the origin. (D) Upper left, SEM of the nanowire structure. Scale bar, 10 μm. Inset, magnified view of one of the bends. Scale bar, 200 nm. Lower left, SOM image. Scale bar, 10 μm. At right, intensity profile along the path indicated in the SOM map. Arrows 1 and 2 designate the locations of the two intrawire bends.

although the radius of the nanowire, 100 nm, provides an upper bound and highlights the sub-wavelength nature of these waveguides and bends. Analysis of the intensity vs position along the nanowire shows that the loss through this abrupt bend is 1−2 dB, after accounting for loss in the straight portion of the nanowire in a manner similar to previous studies of PCs.[7,21,22] The losses observed in the straight sections of this and other nanowires are believed to be due to surface roughness, which can be minimized as evidenced by nearly loss-free transmission in Figure 1B. In addition, SOM characterization of a ca. 55 μm long nanowire containing two abrupt 46 ± 1° bends separated by ca. 6 μm in a Z-type structure (Figure 1D) demonstrates that it is possible to guide light through multiple sub-wavelength bends with only a moderate loss. The intensity vs position data show that there is ca. 1 dB loss or less per abrupt bend in this structure, after accounting for loss in the straight portion of the nanowire. Our results can be compared to a similar double bend PC structure[22] with a waveguide channel approximately 1.5 μm wide, which is comparable to the wavelength of the guided light. The loss per bend in the PC structure, 1.5−3 dB, is similar to our new approach, even though the nanowire guides are operating in a sub-wavelength or nanophotonic regime with 200 nm diameter channel and ca. 515 nm wavelength light and have not been optimized in any manner.

In addition, nanowires can be assembled into crossed and more complex structures[23,24] useful for electronic elements, such as logic gates,[23] and might also function as a flexible structural motif for guiding light around sharp and even acute turns. A SOM image of a single crossed CdS nanowire structure with an angle of 43 ± 1° (Figure 2A) demonstrates that light is guided through the sharp bend defined by the cross. The intensity vs position data (Figure 2B) shows that the loss per unit length including the cross is comparable to losses per unit length in the straight segments of these two

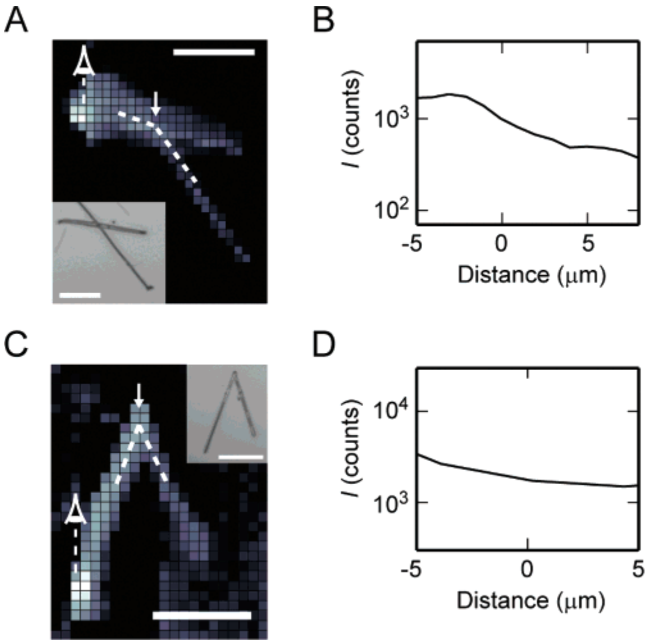

Figure 2. Characterization of assembled nanowire waveguide structures. (A) SOM image of two CdS nanowires assembled in a crossed geometry; inset, optical micrograph. Both scale bars are 10 μm. (B) Intensity profile along the path indicated in (A) with the junction (marked by the white arrow in (A)) set as the origin. (C) SOM image of two CdS nanowires which meet in a nearly end-to-end geometry with an acute angle; inset, optical micrograph. Scale bars are 10 μm. (D) Intensity profile along the path marked in (C) with the junction (marked by the white arrow in (C)) set as the origin.

nanowires, and thus the loss associated with the cross itself is ca. 1 dB (see also, Figure S1, Supporting Information). We have also characterized a related structural motif involving a bend defined by an end-to-end assembly of CdS nanowires (Figure 2C) and find that it exhibits good transmission through the acute angle defined by this assembly. Quantitative analysis of intensity versus position (Figure 2D) further shows that there is no abrupt increase in loss associated with guiding light through this acute angle structure, and that the loss associated with the end-to-end junction is ca. 1 dB.

The above measurements demonstrate that light can be guided or coupled efficiently through sub-wavelength turns defined by junctions between two nanowires. Coupled dielectric waveguides are widely used in photonics,[1,13] although the mechanism and length-scale of coupling are different than in the present nanowire structures. Specifically, coherent transfer of energy between two dielectric waveguides occurs by optical tunneling between parallel sections that are sufficiently close so that evanescent fields overlap and requires transfer over length scales much larger than the wavelength of light, typically on the scale of millimeters.[13] To explain the substantial transfer of energy observed for interaction lengths on the order of 100 nm or a fraction of a wavelength in junctions defined by crossed and end-to-end nanowire structures, we suggest a mechanism involving band gap absorption of the evanescent field and subsequent radiative recombination within the second nanowire waveguide.

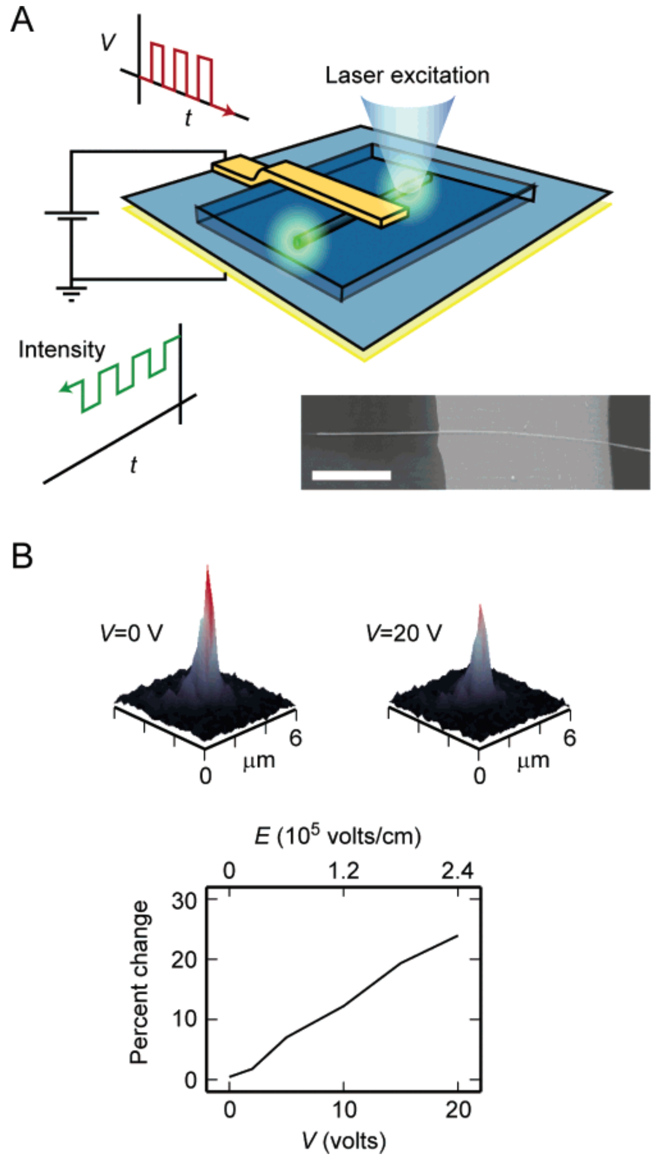

Figure 3. Electrical modulation of light in nanowire waveguides. (A) Schematic of a nanowire EOM. A cw laser source injects light into the nanowire waveguide, and a variable electric field applied across the nanowire using a parallel-plate capacitor geometry modulates the end intensity. Inset, SEM image of a typical device; scale bar is 5 μm. (B) Intensity modulation at the nanowire end. Top, images of the end spot for voltages of 0 and 20 V. Bottom, the change in output intensity as a function of applied voltage; the corresponding electric field (calculated from the electrode separation) is shown on the top axis.

In addition, the combination of active nanowire waveguides with electrical inputs has been investigated to explore integration of additional function. First, light transmission through a nanowire waveguide subject to a time varying electric field applied via a parallel plate capacitor structure (Figure 3A) was characterized. The parallel plate capacitor is composed of a heavily doped silicon substrate and a gold top electrode. The nanowire waveguide is electrically insulated from these electrodes by silicon oxide and polymer, respectively.[25] Increasing the applied voltage V (Figure 3B) yields a significant and reversible decrease in the output intensity at the end of the nanowire. Voltage-dependent measurements (Figure 3B) show a linear decrease up to 20

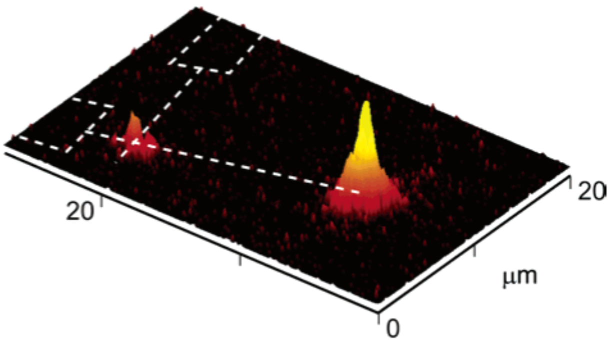

Figure 4. Electrical injection of light into nanowire waveguides. Intensity map of a light-emitting diode made by assembling one *n*-type CdS nanowire and one *p*-type Si nanowire in a crossed geometry. The white dashed lines highlight the positions of the CdS (∼horizontal) and Si (∼vertical) nanowires. The image was recorded with a forward bias of 11 V. Titanium metal electrodes were used to contact both nanowires (dashed white boxes).

V; although deviations from linearity are observed at larger voltages, an attenuation of −3 dB is achieved at 60 V. Studies of devices made with smaller (150 vs 700 nm) electrode separations further confirm that the percentage modulation scales with the electric field (not capacitor voltage). Further studies should aid in assigning the observed electro-optic modulation (EOM) to changes in the refractive index or absorption coefficient.[13] Notably, comparison of our EOMs to recently reported Si-based[26] and InGaAs waveguide[27] modulators shows that the unoptimized nanowire device performance is substantially better than or comparable to more conventional integrated structures: 1 dB/10 μm, nanowire; 0.015 dB/10 μm, Si; and 2.3 dB/10 μm, InGaAs, where all are measured with 10 V modulation voltage. Integrated EOMs, which are important in many photonic systems,[1,13,27] have not yet been reported for 2D photonic crystals or nanoscale plasmonics, but our work suggests nanowire EOMs can be combined now with the nanowire photonic components described above.

Last, we have investigated integrated electrical injection of light into nanowire waveguides from crossed *p*-type and *n*-type materials. Efficient in-coupling has been a challenge for all sub-wavelength waveguides ranging from plasmonic guides and photonic crystals to silicon-on-insulator (SOI) devices. Fiber tapers are often used to couple light from a light source into a passive sub-wavelength waveguide. Active semiconductor nanowires have the unique advantage that they can be used to both generate and waveguide light. Previous studies[28,29] of structures assembled from nanowires with diameters smaller than needed to efficiently serve as waveguides have shown that the *p-n* diodes formed at cross points function as nanoscale light-emitting diodes. Notably, images recorded from forward biased *p-n* diodes fabricated using *n*-CdS nanowires with diameters sufficiently large (i.e., ≥ 80 nm diameter) to function as a good waveguides (Figure 4) demonstrate that while some light is emitted at the cross point, most of the light is emitted from the CdS nanowire end. These data show that the crossed nanowire *p-n* diode structure can couple light efficiently into the guided modes of the nanowire. This device demonstrates efficient in-coupling in nanowire waveguides. This concept could be extended in several important directions in the future, for example, by creating a diode from *p*- and *n*-type CdS waveguides or different direct band gap waveguides such as CdS and CdSe since these structures could then provide two of the same or different frequency sources in a way that could be directly integrated with other nanowire components discussed above.

In summary, we have described an approach for guiding and manipulating light on sub-wavelength scales using active nanowire waveguides and devices. Our quantitative studies have shown that structural motifs based on changes in the axial growth direction of single nanowires and assembled crossed nanowires yield efficient guiding of light through sub-wavelength bends, including acute angles. Importantly, our studies have also shown that electronics can be efficiently combined with the active nanowire waveguides to yield EOMs and efficient nanoscale light-emitting diode injection sources. The basic functions demonstrated in this work open up opportunities in nanophotonics, yet to realize this promise will require further studies clarifying the fundamental properties of these devices and developing efficient methods for assembling more complex structures. Addressing these challenges could make possible the development of nanowire-based photonic circuits and ultimately integrated photonic systems that could impact areas ranging from communications to computing.

Acknowledgment. We thank R. Agarwal, O. Hayden, Y. Wu, and W. Lu for helpful discussions. C.M.L. acknowledges support of this work by the Air Force Office of Scientific Research and Defense Advanced Research Program Agency.

Supporting Information Available: Schematics illustrating scanning optical microscopy (SOM) of nanowire structures and the resulting intensity profiles. This material is available free of charge via the Internet at http://pubs.acs.org.

References

(1) Saleh, B. E. A.; Teich, M. C. *Fundamentals of Photonics*; Wiley: New York, 1991.
(2) Mekis, A.; Chen, J. C.; Kurland, I.; Fan, S.; Villeneuve, P. R.; Joannopoulos, J. D. *Phys. Rev. Lett.* **1996**, *77*, 3787.
(3) Maier, S. A.; Brongersma, M. L.; Kik, P. G.; Meltzer, S.; Requicha, A. A. G.; Atwater, H. A. *Adv. Mater.* **2001**, *13*, 1501.
(4) Joannopoulos, J. D.; Villeneuve, P. R.; Fan, S. H. *Nature* **1997**, *386*, 143.
(5) Qi, M.; Lidorikis, E.; Rakich, P. T.; Johnson, S. G.; Joannopoulos, J. D.; Ippen, E. P.; Smith, H. I. *Nature* **2004**, *429*, 538.
(6) Brongersma, M. L.; Hartman, J. W.; Atwater, H. A. *Phys. Rev. B* **2000**, *62*, R16356.
(7) Lin, S. Y.; Chow, E.; Hietala, V.; Villeneuve, P. R.; Joannopoulos, J. D.; High, J. D. *Science* **1998**, *282*, 274.
(8) Maier, S. A.; Kik, P. G.; Atwater, H. A.; Meltzer, S.; Harel, E.; Koel, B. E.; Requicha, A. A. G. *Nature Mater.* **2003**, *2*, 229.
(9) Huang, M.; Mao, S.; Feick, H.; Yan, H.; Wu, Y.; Kind, H.; Weber, E.; Russo, R.; Yang, P. *Science* **2001**, *292*, 1897.
(10) Johnson, J. C.; Yan, H. Q.; Yang, P. D.; Saykally, R. J. *J. Phys. Chem. B* **2003**, *107*, 8816.
(11) Duan, X.; Huang, Y.; Agarwal, R.; Lieber, C. M. *Nature* **2003**, *421*, 241.
(12) Tong, L.; Gattass, R.; Ashcom, J.; He, S.; Lou, J.; Shen, M.; Maxwell, I.; Mazur, E. *Nature* **2003**, *426*, 816.

(13) Hunsperger, R. G. *Integrated Optics*; Springer-Verlag: New York, 2002.
(14) Manolatou, C.; Johnson, S. G.; Fan, S.; Villeneuve, P. R.; Haus, H. A.; Joannopoulos, J. D. *J. Lightwave Technol.* **1999**, *17*, 1682.
(15) Ahmad, R. U.; Pizzuto, F.; Camarda, G. S.; Espinola, R. L.; Rao, H.; Osgood, R. M. *IEEE Photonics Technol. Lett.* **2002**, *14*, 65.
(16) Duan, X.; Lieber, C. M. *Adv. Mater.* **2000**, *12*, 298.
(17) Barrelet, C. J.; Wu, Y.; Bell, D. C.; Lieber, C. M. *J. Am. Chem. Soc.* **2003**, *125*, 11498.
(18) CdS nanowires were synthesized using gold nanoclusters (Ted Pella, Inc., Redding, CA) as catalysts, and either a single-source molecular precursor (cadmium diethyldithiocarbamate, Lorad Chemical Co., St. Petersburg, FL) or laser ablation of a solid CdS target as a reactant source. Bent nanowires were prepared by raising the growth temperature by 40 °C above the optimal value for purely axial growth. An upper bound for the diameter variation, ΔD, in the nanowire waveguides is ca. 1 nm over 10 μm length L, giving $\Delta D/\mathrm{L} = 0.0001$.
(19) Studies suggest that modulation of the temperature or pressure during growth can yield abrupt bends along the nanowire axis in a controlled manner (Z. Zhong, C. Yang, and C. M. L., unpublished data).
(20) Nanowires dispersed in ethanol were deposited on Si wafer substrates with a 600 nm thermal oxide. Photoluminescence (PL) images were obtained using a far-field epifluorescence microscope equipped with a liquid nitrogen cooled charge coupled device (CCD) camera. Laser excitation (488 nm) was focused through the objective (NA = 0.7) to a diffraction-limited spot on the sample surface, providing a typical excitation power density of ~1000 kWcm^{-2}. SOM images were recorded by determining the intensity at the nanowire end from a series of PL images, which were obtained by scanning the sample beneath the laser spot. The resolution in these experiments, 1 μm, was determined by the $x-y$ sample scanning stage.
(21) The intensity profile along the nanowire is used to quantify the loss in these waveguides. The loss between two points reported in decibels is given by $10 \times \log(I_1/I_2)$, where I_1 and I_2 correspond to the end intensity recorded with the laser at the two different positions along the waveguide. In this manner (Figure S1), the loss due to a bend or junction was estimated by comparing the loss observed in two segments of equal length along the waveguide: one along a straight section and the other containing the bend or junction.
(22) Talneau, A.; Le Gouezigou, L.; Bouadma, N.; Kafesaki, M.; Soukoulis, C. M.; Agio, M. *Appl. Phys. Lett.* **2002**, *80*, 547.
(23) Huang, Y.; Duan, X.; Wei, Q.; Lieber, C. M. *Science* **2001**, *291*, 630.
(24) Whang, D.; Jin, S.; Wu, Y.; Lieber, C. M. *Nano Lett.* **2003**, *3*, 1255.
(25) Devices were fabricated on a heavily doped Si substrate, which serves as the lower electrode, with a thermal oxide layer. The nanowire is deposited on the oxide, covered with a cross-linked poly(methyl methacrylate) (PMMA) layer, and then the Au top electrode is patterned by electron-beam lithography (EBL).
(26) Liu, A. S.; Jones, R.; Liao, L.; Samara-Rubio, D.; Rubin, D.; Cohen, O.; Nicolaescu, R.; Paniccia, M. *Nature* **2004**, *427*, 615.
(27) Souza, P. L.; Pires, M. P.; Yavich, B.; Racedo, F.; Tribuzy, C. V.-B. *Microelectron. J.* **2002**, *33*, 341.
(28) Duan, X.; Huang, Y.; Cui, Y.; Wang, J.; Lieber, C. M. *Nature* **2001**, *409*, 66.
(29) Zhong, Z.; Qian, F.; Wang, D.; Lieber, C. M. *Nano Lett.* **2003**, *3*, 343.

NL048739K