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Assembly of Silica Nanowires on Silica Aerogels for Microphotonic Devices

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ABSTRACT

We report on the assembly of low-loss silica nanowires into functional microphotonics devices on a low-index nondissipative silica aerogel substrate. Using this all-silica technique, we fabricated linear waveguides, waveguide bends, and branch couplers. The devices are significantly smaller than existing comparable devices and have low optical loss, indicating that the all-silica technique presented here has great potential for future applications in optical communication, optical sensing, and high-density optical integration.

Conventional approaches for miniaturizing photonic devices with subwavelength, nanometer-scale optical guiding structures are hampered by the ultrahigh-precision requirements of functional devices and the high cost associated with fabrication techniques such as X-ray lithography.[1−3] Moreover, the high optical losses of currently achievable nanometer-scale guiding structures such as surface plasmon waveguides severely limit their applications.[4−6] For example, low optical loss of the guiding structure is essential to obtain a high Q-factor in an optical microcavity resonator,[7] to maintain the coherence of the guided light in optical waveguide/fiber sensors using coherent detection,[8−10] to reduce the noise or cross talk in high-density optical integration, and to reduce energy consumption when many devices are connected in series. Recently, subwavelength semiconductor nanowire waveguides were produced and assembled into various geometries including bends, filters, and active devices.[11,12] However, the semiconductor waveguides have substrate-induced radiation losses on the order of several dB/mm; for thin ribbons, the maximum length over which red light can be propagated is 100 μm.[11] Here we report on an all-silica method for assembling low-loss nanometer-scale wire waveguide building blocks into functional microphotonics devices on a solid substrate. After trimming highly uniform silica nanowires into micrometer-sized pieces, we shape and then assemble these pieces on low-index nondissipative silica aerogel to form basic devices including linear waveguides, waveguide bends, and branch couplers.

We previously reported on the fabrication of long, freestanding silica wires with nanometer-scale diameters using a taper drawing technique.[13] Scanning electron microscope (SEM) and transmission electron microscope (TEM) images show that these submicrometer- or nanometer-diameter wires (SMNWs) have excellent diameter uniformity and atomic-level sidewall smoothness. We demonstrated that freestanding SMNWs allow low-loss effective single-mode waveguiding of visible and near-infrared light.[13]

To use these SMNWs as building blocks for integrated microphotonic devices, a number of important challenges must be overcome.[14] First, micromanipulation techniques must be developed to finely tailor them into the desired micrometer-sized geometries. Second, the wires must be mounted on a substrate without losing their optical wave guiding properties. Finally, optical shorts between adjacent wires must be prevented. In this letter we report on a method for assembling microphotonic devices that meets all of these challenges, while still maintaining the simplicity of the original fabrication process.

Using scanning tunneling microscope (STM) probes, the silica SMNWs can be cut, positioned, bent, and twisted with high precision under an optical microscope. To cut a SMNW to a desired length, for example, we apply a bend-to-fracture method by holding the wire with two STM probes on a silicon or sapphire substrate and using a third probe to bend the wire to fracture at the desired point. This process leaves

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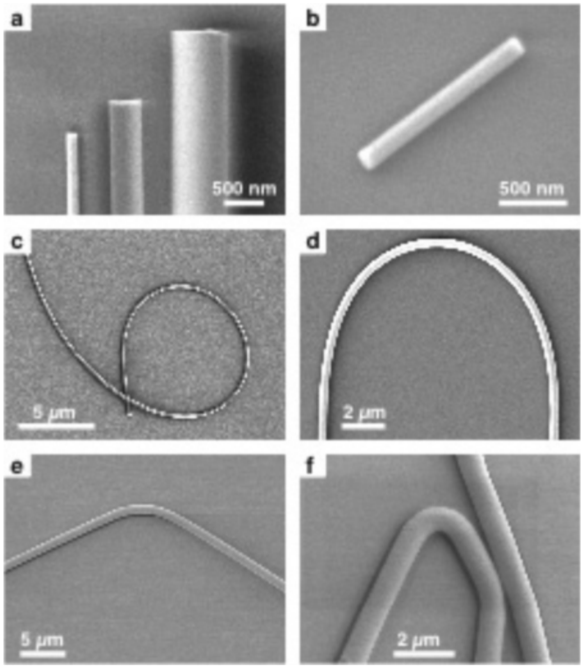

Figure 1. SEM images of waveguide building blocks made from silica SMNWs. (A) 140-, 420-, and 680-nm diameter wires with flat end faces. (B) A 1.5-μm long segment cut from a wire of 160-nm diameter. (C) A 9-μm diameter loop on a sapphire substrate formed by elastic bending of a 200-nm diameter wire. (D) A plastic bend in an annealed 410-nm diameter wire on a sapphire substrate. (E) Double plastic bends in a 940-nm diameter wire. (F) Double bend in an 800-nm diameter wire. The sharp bend has a radius of less than 1 μm.

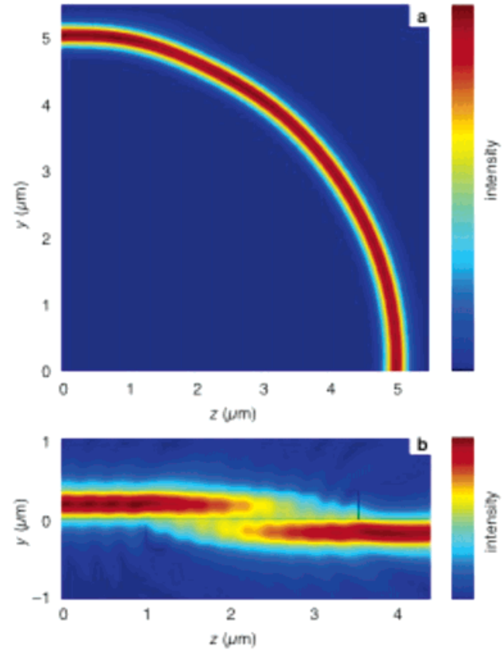

Figure 2. 3D-FDTD simulations of the guiding properties of silica SMNWs. The electric fields are polarized perpendicular to the paper; the intensity is plotted on a logarithmic scale. (A) Light intensity distribution in a 5-μm radius bend of a 450-nm diameter wire. (B) Evanescent coupling between two 350-nm diameter silica wires.

flat end faces at the fracture point (Figure 1A and 1B), even for a segment of just 1 μm in length (Figure 1B). When pieces of silica wires are placed on a substrate, they are held tightly in place by the van der Waals attraction between the wire and the substrate. The wire can then be repositioned or elastically bent to a desired radius using STM probes. Figure 1C, for example, shows a 200-nm diameter wire bent into a 9-μm diameter loop on a sapphire wafer. The shape of the loop is maintained after removing the STM probes because of the friction between wire and the substrate. To avoid long-term fatigue and fracture of an elastically bent wire due to bending stress,[15,16] we anneal the bent wire for 2 h at 1400 K in vacuum (2×10^{-3} Pa), leaving a permanent plastic deformation without change in surface smoothness or diameter uniformity. Because the elastically bent wire is held tightly on the substrate, the geometry of the assembly is not affected by the annealing, making it possible to lay out a final design before annealing. Figure 1D shows a 5-μm radius plastic bend in a 410-nm wide wire on a sapphire substrate. The difference in bending radii before and after the annealing is less than 0.5%. This annealing-after-bending process can be performed repeatedly to obtain very tight bends or multiple bends in nearby locations (Figure 1E and 1F).

The optical wave guiding properties of these wires can be obtained by solving the Maxwell equations numerically.[17,18] When the normalized wire diameter D/λ_o falls below 0.73, only a single mode can propagate through the wire. At the single-mode cutoff diameter D_{SM} (457 nm for 633-nm light), more than 80% of the light energy is guided inside the wire. The remainder is guided as an evanescent wave. This tight confinement reduces losses in a sharp bend. For example, Figure 2A shows the intensity distribution of the electric field on the cross-section of a 450-nm diameter wire bent to a radius of 5 μm. The intensity distribution, obtained using a three-dimensional finite-difference time-domain (3D-FDTD) calculation,[19] shows that there is virtually no leakage of light through such a tight bend. Despite the tight confinement, the large evanescent wave outside the wire facilitates coupling of light from one wire to another. Figure 2B shows a 3D-FDTD simulation of the evanescent coupling of 633-nm light between two 350-nm-diameter wires with an overlap of only 2.6 μm. More than 97% of the light energy is transferred from the upper wire to the bottom one. This very efficient coupling makes it possible to launch light conveniently into these thin silica wires, to couple light efficiently between wires, and to build micrometer-sized optical couplers.

To assemble microphotonic devices from silica nanowires, the wires must be supported by a substrate. The relatively low index of silica (about 1.45), however, necessitates a substrate with an index much lower than 1.45. We address this problem by using silica aerogel as a substrate. Silica aerogel is a tenuous porous silica network of silica nanoparticles of about 30 nm in size, much smaller than the wavelength of the guided light, and has a transparent optical spectral range similar to that of silica.[20,21] Because the aerogel is mostly air, its refractive index is very close to that of air. Figure 3A shows a close-up view of a 450-nm diameter silica wire supported on a substrate of silica aerogel. Because the index difference between the silica aerogel and air (about 0.03) is much lower than the index difference between the

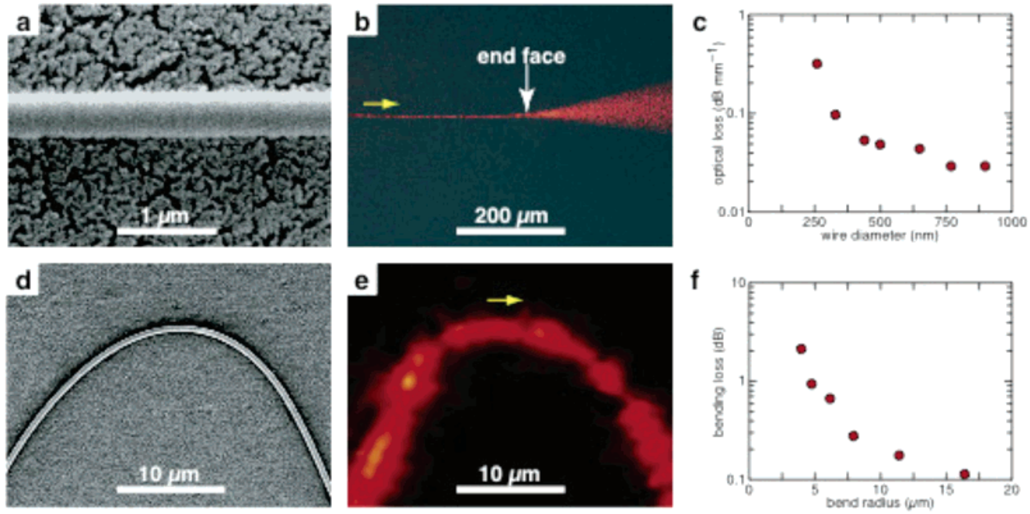

Figure 3. Guiding of light by straight and curved silica wires mounted on silica aerogel. (A) SEM image of a 450-nm wide silica wire supported by silica aerogel. (B) Optical microscopy image of a 380-nm diameter silica wire guiding 633-nm wavelength light on the surface of silica aerogel. The green arrow indicates the direction of light propagation; at the right end of the wire, the light spreads out and scatters on the aerogel surface. (C) Measured optical loss of straight aerogel-supported wires at a wavelength of 633 nm. (D) SEM image of an aerogel-supported 530-nm wide wire with a bending radius of 8 μm. (E) Optical microscopy image of an aerogel-supported 530-nm wide wire guiding light around a bend with a radius of 8 μm. (F) Measured bending loss in a 90° bend in aerogel-supported 530-nm wide wires at a wavelength of 633 nm.

silica SMNW and air (about 0.45), the optical guiding properties of aerogel-supported wires are virtually identical to those of air-clad ones. To study the optical properties of aerogel-supported wires, we couple light into the core of a single-mode fiber that is tapered down to a nanowire. The nanowire taper is used to evanescently couple the light into aerogel-supported wires by overlapping the two in parallel on the aerogel surface (see Figure 2B). We obtain coupling efficiencies as high as 95%, giving a connection loss of less than 0.3 dB, and the supported wires guide light with low optical loss. Figure 3B shows a 380-nm-diameter silica wire guiding 633-nm-wavelength light on the surface of a silica aerogel substrate. The uniform and virtually unattenuated scattering along the nearly 0.5-mm length of the wire and the strong output at the end face show that the scattering is small relative to the guided intensity. Figure 3C shows the measured loss of silica wires supported by an aerogel substrate. To determine the loss, we used the same method as for air-clad SMNWs.[13] We obtained lower losses than those we reported previously[13] for air-clad SMNWs because we more carefully controlled contamination of the wires from the atmosphere. The low loss provides further evidence that the aerogel substrate does not degrade the guiding of light through the SMNWs. For wires with a diameter near D_{SM}, the loss is less than 0.06 dB/mm, which is much lower than the optical loss in other subwavelength-structures.[4−6,11] This low loss makes silica aerogel supported SMNWs attractive building blocks for microphotonic devices.

Figure 3D shows plastically bent wire of 530-nm diameter on a silica aerogel substrate. The wire was first bent to a radius of about 8 μm on a sapphire wafer, annealed, and then transferred to silica aerogel. These aerogel-supported plastic bends show excellent optical wave guiding with good confinement of the light. Figure 3E, for example, shows an optical microscope image of 633-nm wavelength light guided through such an aerogel-supported plastic bend. The measured bending losses (Figure 3F) through a 90° bend in a 530-nm diameter wire are small enough to be acceptable for photonics devices. For example, the optical loss around a 5-μm radius bend in a 530-nm diameter wire is less than 1 dB. Bending waveguides based on planar photonic crystal structures[22−24] not only require multiple periods (which increase the overall size) and sophisticated fabrication techniques but they also have inevitable out-of-plane loss. In contrast, the SMNW bends of the type illustrated in Figure 3 offer the advantages of compact overall size, low coupling loss, simple structure and easy fabrication. We also verified that light can be guided over a broad range of wavelengths within the absorption edges of silica,[25] just like silica nanowires obtained with other taper drawing techniques.[26−30] Specifically, we confirmed transmission at the following wavelengths: 325, 442, 514, 633, 800, and 1550 nm. Contrary to wavelength-specific photonic crystal structures, SMNW bends can be used over a broad range of wavelengths, from the near-infrared to ultraviolet wavelengths.

Using waveguide bends as building blocks, one can readily assemble basic microphotonic devices on a silica aerogel substrate. Figure 4A shows an X-coupler assembled from two 420-nm diameter silica wire bends. When 633-nm wavelength light is launched into the bottom left arm, the coupler splits the flow of light in two. With an overlap of less than 5 μm, the device works as a 3-dB splitter with an excess loss of less than 0.5 dB. Microscopic couplers such as fused couplers, made from fiber tapers using conventional methods, require an interaction length on the order of 100 μm.[31] In comparison, couplers assembled with SMNWs reduce the device size by more than an order of magnitude. By changing the overlap between the two bends over a range of about 3 μm, we were able to tune the splitting ratio of such a coupler from less than 5% to more than 90%. This

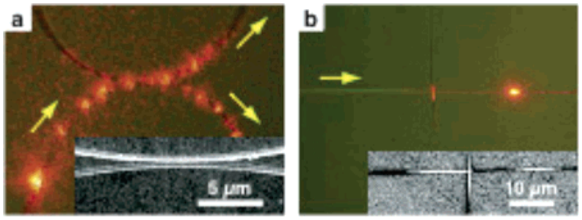

Figure 4. Optical coupling between aerogel-supported silica wires. The green arrows indicate the direction of light propagation. (A) Optical microscope image of a micrometer-scale X-coupler assembled from two 420-nm wide silica wires. The two wires overlap less than 5 μm at the center (see SEM image in inset). The assembly acts as a 3-dB splitter for light launched into the bottom left branch. (B) Two 390-nm wide silica wires intersect perpendicularly on the surface of an aerogel substrate. There is virtually no crosstalk between the two wires. Inset: SEM close-up of intersection.

wire-assembly process thus makes it feasible to develop tunable microphotonic devices, such as tunable couplers and switches.

We also investigated the cross-talk of two intersecting wires supported on silica aerogels. Figure 4B shows two 390-nm diameter silica wires that intersect vertically on a silica aerogel substrate. When a 633-nm-wavelength light is launched along the horizontal wire, no light couples to the vertical wire, except for some weak scattering that occurs at the intersection. The intentionally induced strong scattering on the right side of the horizontal wire gives a feel for the relative intensity of the guided light. The measured cross-talk of the two wires in Figure 4B is about −35 dB, and thicker wires show even better "isolation". Even though light can easily be exchanged between subwavelength-diameter wires with a "simple touch"− just like the electrical contact between two conducting wires− vertically intersecting wires do not cause an "optical shortcut." This lack of cross talk between vertically intersecting wires is a very desirable property for high-density optical integration.

Because silica is one of the fundamental materials for photonics, the all-silica wire-assembly method presented here can also be applied to doped wires to form active devices and other types of nanostructured substrates with suitable dielectric properties (e.g., mesoporous materials[32−34]). Given that linear waveguides, waveguide bends, and branch couplers are the basic components of optical circuits and photonic devices, this work paves the way for the development of a variety of flexible microphotonic devices of significantly reduced size.

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