Subwavelength-diameter silica wires for microscale optical components

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ABSTRACT

Subwavelength-diameter silica wires fabricated using a taper-drawing approach exhibit excellent diameter uniformity and atomic-level smoothness, making them suitable for low-loss optical wave guiding from the UV to the near-infrared. Such air-clad silica wires can be used as single-mode waveguides; depending on wavelength and wire diameter, they either tightly confine the optical fields or leave a certain amount of guided energy outside the wire in the form of evanescent waves. Using these wire waveguides as building blocks we assembled microscale optical components such as linear waveguides, waveguide bends and branch couplers on a low-index, non-dissipative silica aerogel substrate. These components are much smaller than comparable existing devices and have low optical loss, indicating that the wire-assembly technique presented here has great potential for developing microphotonics devices for future applications in a variety of fields such as optical communication, optical sensing and high-density optical integration.

Keywords: Subwavelength, silica, nanowire, microphotonics, nanophotonics, optical components

1. INTRODUCTION

Optical components built from structures that are tens of micrometers wide are playing a key role in current optical communication networks, optical sensors, and medical optical devices.[1-3] The demand for improved performance, broader applications, and higher integration density, together with rapid advances in nanotechnology for electronics and optoelectronics, has spurred an effort to reduce the size of basic optical components. However, the miniaturization of optical components with subwavelength and nanometer-sized optical wave guiding structures through established fabrication methods is limited by the requirements of submicrometer precision and the high cost associated with fabrication techniques such as EUV, X-ray and e-beam lithography.[4-6] In addition, the high optical losses of current nanometer-sized waveguides (*e.g.*, surface plasmon waveguides) severely limit their applications.[7-9]

We recently developed a new type of optical wave guiding structure — subwavelength-diameter silica wires — as low-loss nanometer-sized building blocks for microscale optical components.[10-12] By means of a simple high-temperature drawing/tapering approach, we fabricate highly uniform silica wires as thin as 50 nm with surface roughness less than 0.5 nm (RMS). Within the visible and near-infrared spectral ranges, these wires can be used as subwavelength-diameter single-mode waveguides with optical losses down to 0.03 dB/mm, which is low enough for building microscale optical components. Using high-precision micro-/nano-manipulators, we assemble basic components such as waveguide bends and optical couplers from silica wires. We also investigate properties of these wires that are relevant for practical applications, such as their mechanical strength, their wave guiding properties on a low-index support and the cross talk between such wires. Both theoretical and experimental results show that the subwavelength-diameter silica wires reported here are promising and versatile building blocks for microscale optical components of significantly reduced size.

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2. SILICA NANOWIRES FROM TAPER DRAWING

A number of techniques have recently been reported for bottom-up synthesis of silica nanowires with diameters down to 10 nm.[13-18] However, most of these chemically grown wires are unsuitable for low-loss optical wave guiding because of relatively large diameter fluctuations and sidewall roughness. Recently, we demonstrated that a top-down taper-drawing approach can yield silica nanowires with extraordinary uniformity,[10] permitting the use of subwavelength-diameter wires as low-loss optical waveguides.

Compared to most other methods, the taper drawing approach is simple. First, we use a flame or carbon oxide laser beam to draw a standard glass fiber (*e.g.*, SMF28, Corning Inc.) to a micrometer-diameter wire. Second, to further reduce the wire diameter and maintain a steady temperature distribution in the drawing region, we use a tapered sapphire fiber of about 100 µm in diameter to absorb the flame energy and generate an appropriate temperature distribution. As illustrated in Fig. 1, after the flame is adjusted so that the temperature of the sapphire tip is a bit higher than the drawing temperature (about 2000 K), we place one end of a micrometer-diameter silica wire horizontally on the sapphire tip and rotate the tip around its axis of symmetry so as to wind the silica wire around it. Then we draw the wire perpendicular to the axis of the sapphire tip in the horizontal plane at a speed of 1–10 mm/s. When the drawing is completed, the nanowire is connected to the starting wire at one end and free-standing on the other end. We use a homemade CH_3OH torch burning in air with a nozzle-diameter of about 6 mm. Because the working temperature is below the melting temperature of sapphire (about 2320 K), the sapphire tip can be used repeatedly.

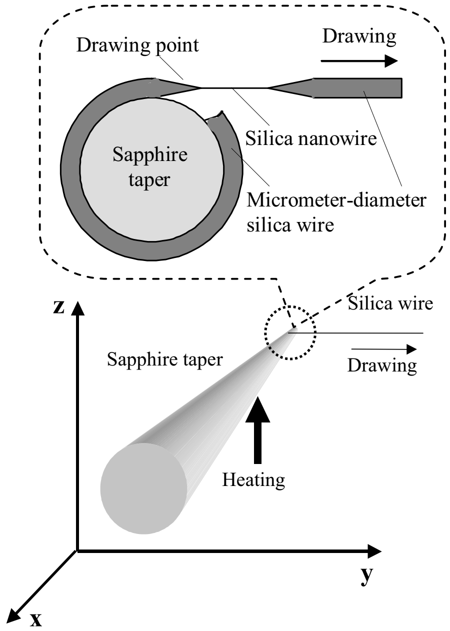

Figure 1. Fabrication of silica nanowires using a taper drawing process. After one end of a micrometer-diameter wire is wound around a heated sapphire taper, a silica nanowire is formed by horizontal drawing.

Using this technique, we obtained long silica nanowires with diameters ranging from 50 nm to several micrometers. Generally, the wire starts from a tapered transition region connected to the starting wire with a length of millimeters. The main part of the wire, with a length from millimeters to tens of millimeters, has excellent diameter uniformity and surface smoothness. Figure 2A shows scanning electron microscope (SEM) images of silica nanowires with diameters ranging from 230 to 660 nm. The SEM images also show the excellent uniformity and smoothness of the wires. Figure 2B shows a SEM image of a 260-nm diameter nanowire of 4.5-mm length. The wire is coiled up to show its length. The maximum diameter variation $\Delta D/L$ is about 2×10^{-6}, with a maximum diameter variation ΔD of about 8 nm over a length L of 4.5 mm. Figure 2C shows the circular cross-section of a 480-nm diameter wire. The perfect cylindrical geometry of the wires makes it possible to obtain their guiding modes by solving Maxwell's equations analytically.[11] We investigated the sidewall roughness of the nanowires using transmission electron microscopy (TEM). Figure 2D shows a typical TEM image of the sidewall of a 300-nm diameter wire. The electron diffraction pattern shown in the inset indicates that the wire is amorphous, just like the starting material. The typical sidewall root mean square (RMS) roughness is less than 0.5 nm, much lower than those of submicrometer wide wires, strips or other structures obtained using other fabrication methods.[13-21] Considering that the length of Si-O bond is about 0.16 nm,[22] such a roughness indicates an atomic-level smoothness of the wire surface.

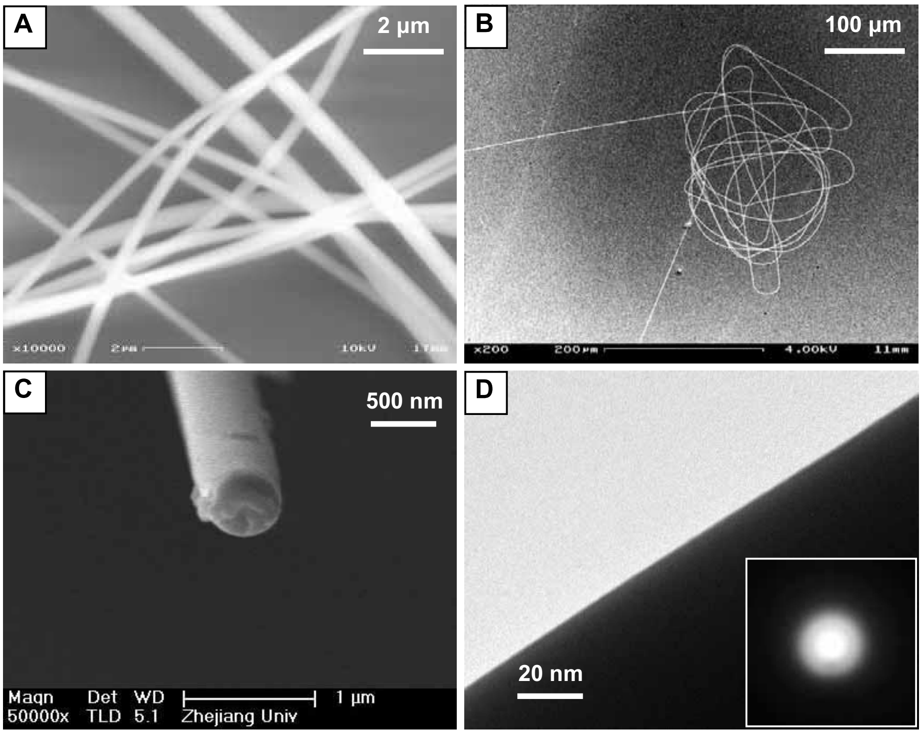

Figure 2. Electron micrographs of silica nanowires. (A) SEM image of silica nanowires with diameters of 230, 260, 280, 330, 360, 400, 520, 570, and 660 nm. (B) SEM image of a 260-nm diameter silica nanowire of 4.5-mm length. (C) SEM image of the cross section of a 480-nm-diameter silica nanowire. (D) TEM image of the edge of a 300-nm-diameter silica wire. Inset: electron diffraction pattern.

3. OPTICAL WAVE GUIDING WITH SILICA NANOWIRES

The optical wave guiding behavior of these subwavelength diameter wires in air can be obtained by numerically solving Maxwell's equations.[11, 23] Figure 3A shows the normalized propagation constants or effective index β/k_o, where β is the propagation constant and $k_o = 2\pi/\lambda_o$, of the first four modes in air-clad wires. When the normalized wire diameter D/λ_o falls below 0.73, the wire is a single-mode waveguide. Figure 3B shows the fractional power of the fundamental mode (HE_{11}) inside the silica core at two typical wavelengths (633- and 1550- nm). For example, at the single-mode cut-off diameter (D_{SM}), more than 80% of the light energy is guided inside the wire, demonstrating its tight-confinement ability. When the wire diameter is reduced to $0.5D_{SM}$ (*e.g.*, 229 nm for light of 633-nm wavelength), about 86% of the light power propagates outside the wire as an evanescent wave. For comparison, Figs. 3C and 3D show the Poynting vector for the fundamental mode at 633-nm wavelength along the direction of propagation for wire diameters of 457 nm (D_{SM}) and 229 nm (0.5 D_{SM}), respectively. Tight confinement reduces bending losses in sharp bends. Weak confinement, on the other hand, facilitates light coupling from one wire to another, and is advantageous for building optical couplers with small size.

To experimentally investigate the guiding properties of the silica nanowires, we send light into them using an evanescent coupling method (Fig. 3E). Light is first sent into the core of a single-mode fiber that is tapered down to a nanowire and the nanowire taper is then used to evanescently couple the light into another one by overlapping the two in parallel. Because of electrostatic and van der Waals forces wires attract one another, making a contact connection. The coupling efficiency of this evanescent coupling can be as high as 90% when the wire diameter and overlap length are properly selected. Because of the nanowires' extraordinary uniformity, the optical loss of these nanowires is extremely low. Figure 3F, for example, shows a 400-nm-diameter silica wire guiding light of 633-nm wavelength from bottom left. The light is intercepted at the top right by a supporting fiber to show that the amount of light scattered by the wire is small compared to that guided by it. The optical loss of these wires measured at D_{SM} (*e.g.*, about 1100 nm at a wavelength of 1550 nm) has recently been reported to be below 0.01dB/mm,[24,25] which is much lower than the optical loss of other subwavelength-structures such as metallic plasmon waveguides or nanowires fabricated by chemical growth.[7-9,26,27]

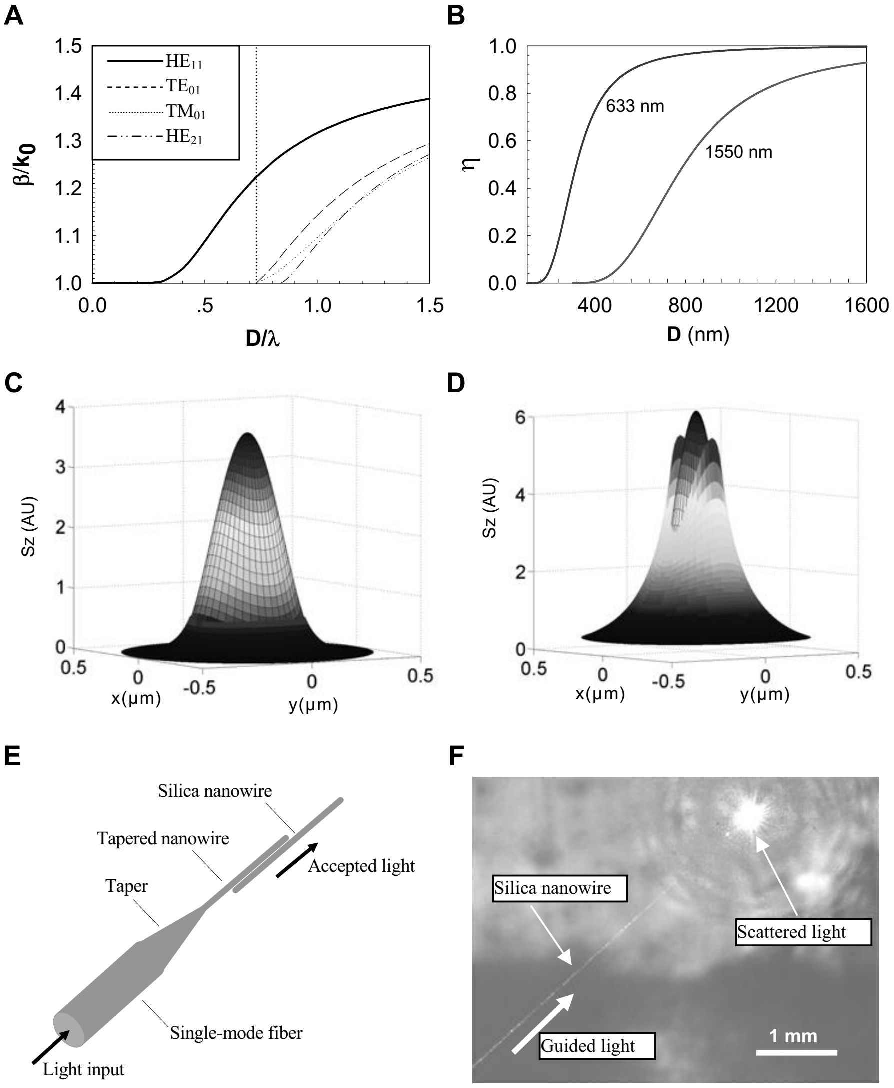

Figure 3. Optical wave guiding properties of air-clad silica nanowires. (A) Normalized propagation constants β/k_0 for the first four modes. The dotted line indicates the single-mode cut-off condition. (B) Fractional power of the HE_{11} mode inside the core at wavelengths of 633 and 1550 nm. z-component of the Poynting vector in wires of (C) 457- and (D) 229-nm diameter at a wavelength of 633-nm wavelength. Mesh, inside silica core; gradient, outside core. (E) Launching light from a fiber taper into a silica nanowire by means of evanescently coupling. (F) A 400-nm diameter silica wire guiding light of 633-nm wavelength light from bottom left. The light is intercepted at the top right by a supporting fiber to show that the amount of light scattered by the wire is small compared to that guided by it.

4. ASSEMBLY OF SILICA NANOWIRES FOR MICROSCALE OPTICAL COMPONENTS

In order to use silica nanowires as building blocks for microscale optical components, the wires must be customized into the desired micrometer-sized geometries, and be supported without losing their optical guiding properties.

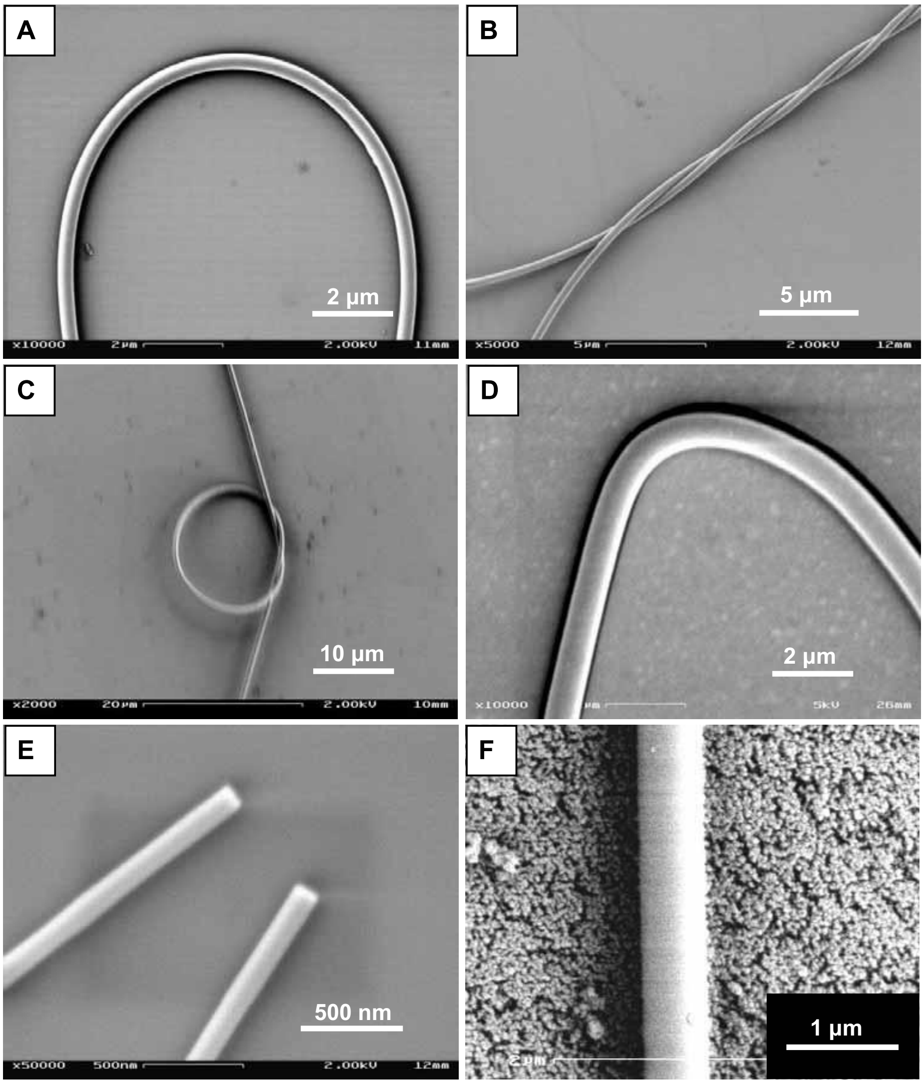

Figure 4. SEM images of silica nanowires patterned with micromanipulation. (A) A bend of 4.2-µm radius formed with a 400-nm diameter silica nanowire. (B) Two twisted 400-nm-diameter silica nanowires. (C) A 14.5-µm diameter ring made with a silica nanowire of 520-nm diameter. (D) A sharp plastic bend made with a 800-nm diameter silica wire. (E) Flat end faces of 125-nm diameter silica nanowires cut using a bend-to-fracture method. (F) Close-up view of a 530-nm-diameter wire mounted on a silica aerogel substrate.

Because of their large length, silica nanowires obtained by the taper drawing method can easily be seen under an optical microscope, even when the wire diameter is below 100 nm. This optical visibility of the nanowire makes it possible to manipulate the silica nanowires in air, greatly facilitating the handling and assembly of these nanowires. Also, because of their excellent uniformity, these wires have high mechanical strength and pliability. Using probes from a scanning tunneling microscope (STM) for holding and manipulating the wires under an optical microscope, we assembled silica nanowires into various patterns. Figures 4A through 4C, for example, show a bend, a twist and a ring assembled from nanowires. The wires do not break when bent and/or twisted, indicating that they have high mechanical strength and flexibility. Using the Young's modulus of silica (about 73 GPa[22]), we find that the tensile strength of the wire shown in Fig. 4A is at least 4.5 GPa. Using plastic bending by a repeated annealing-after-bending process, we can achieve much sharper bends, as shown in Fig. 4D. Silica nanowires can also be cut with high precision under optical microscopes. To cut a wire to a desired length, we hold 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 flat end faces at the fracture point, as shown in Fig. 4E.

To support the nanowire waveguides for device applications, we use silica aerogel as a low-index non-dissipative 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.[28,29] Because the aerogel is mostly air, its refractive index (about 1.03 at a wavelength of 633 nm) is very close to that of air. Figure 4F shows a close-up view of a silica wire of 530-nm diameter 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 silica nanowire and air (about 0.45), the optical guiding properties of aerogel-supported wires are virtually identical to those of the air-clad ones that discussed in Section 3 (see Fig. 3).

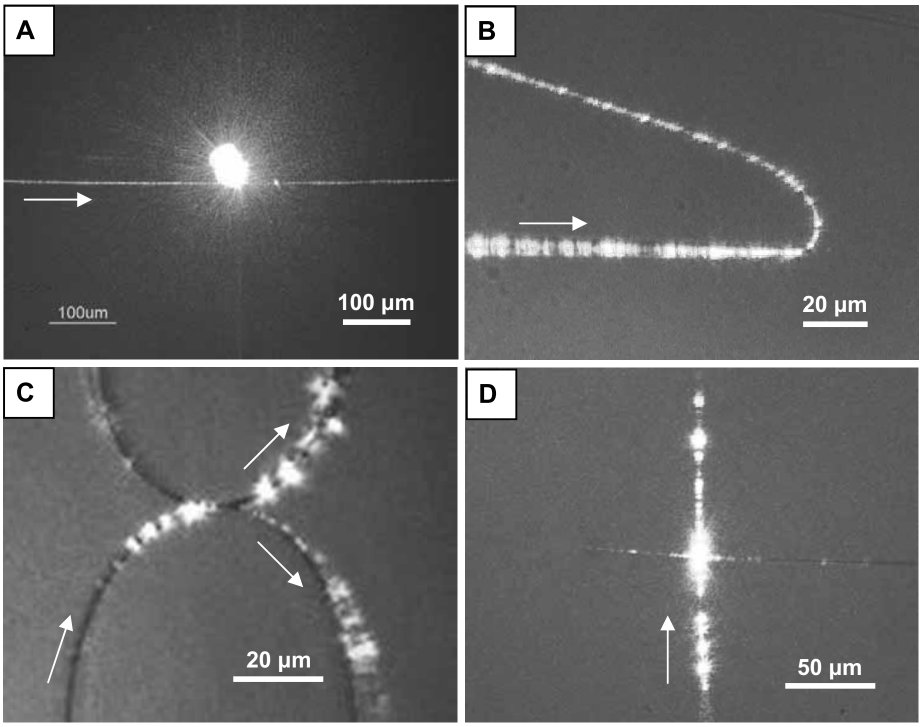

Figure 5. Assembly of silica nanowires on silica aerogel for microscale optical components. All images are taken under an optical microscope, and the guided light comes from a He-Ne laser operating at 633 nm. The arrows in the images indicate the direction of light propagation. (A) Linear waveguide: a 360-nm diameter silica wire guiding light (from left to right) on the surface of silica aerogel. (B) Waveguide bend: an aerogel-supported 530-nm wide wire guiding light around a bend with a radius of 6.8 μm. (C) X-coupler: micrometer-scale optical coupler assembled from two 410-nm wide silica wires. The two wires overlap less than 5 μm at the center. The assembly acts as a 40/60 splitter for light launched into the bottom left branch. (D) Cross talk: A 400-nm and 430-nm diameter silica wires intersect on the surface of an aerogel substrate. Crosstalk between the two wires is very weak.

To investigate the optical properties of aerogel-supported nanowires, we launch light into the wires by evanescent coupling (as illustrated in Fig. 3E) on the aerogel surface. The aerogel-supported silica wire guides light with low optical loss. Figure 5A shows a silica wire of 360-nm diameter guiding light of 633-nm wavelength on the surface of a silica aerogel substrate. The uniform scattering along the length of the wire demonstrates that the optical loss of guided light is low. To illustrate how much higher the guided intensity is compared to the scattered light, we intercept the guided light using a small piece of glass (shown at the center of the image). For wires with a diameter around D_{SM}, the measured optical loss of aerogel-supported nanowires is typically less than 0.06 dB/mm, which is much lower than the optical loss in other subwavelength-structures.[7-9,26,27]. This low loss makes silica-aerogel-supported nanowires suitable for microphotonic devices.

To make a waveguide bend, we first anneal an elastically bent wire on the surface of a sapphire substrate, and then transfer it to silica aerogel. Figure 5B shows an optical microscope image of 633-nm wavelength light guided through an aerogel-supported plastic bend in a silica wire of 530-nm diameter. The measured bending loss of this 6.8-µm radius bend is less than 0.7 dB, which is small enough for microphotonic circuits. By comparison, bending waveguides based on planar photonic crystal structures not only require multiple periods (which increase the overall size) and sophisticated fabrication techniques,[30-33] but they also have inevitable out-of-plane loss. In contrast, aerogel-supported wire bends offer the advantages of compact overall size, low coupling loss, simple structure and easy fabrication. Also, contrary to wavelength-specific photonic crystal structures, nanowire 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 devices such as optical couplers. Figure 5C, for example, shows an X-coupler assembled from two silica wire bends of 410-nm diameter. When light of 633-nm wavelength is launched into the bottom left arm, the coupler splits the flow of light into two. With an overlap of less than 5 μm, the device works as a 40/60 splitter. Microscopic couplers such as fused couplers, made from fiber tapers using conventional methods, require an interaction length on the order of 100 µm.[34] By comparison, couplers assembled with silica nanowires reduce the device size by more than an order of magnitude.

We also investigated the cross-talk of two intersecting wires. Figure 5D shows two silica wires of a 400-nm and 430-nm diameter that intersect nearly perpendicularly on the surface of a silica aerogel substrate. When 633-nm wavelength light is guided along the vertical wire, no light couples to the horizontal one, except for some weak scattering that occurs at the intersection. The measured cross-talk of the two wires is less than –26 dB, and thicker wires show even better “isolation”. This very weak cross talk between vertically intersecting wires represents another favorable property for high-density optical integration.

4. CONCLUSIONS

In conclusion, we presented a new type of subwavelength-diameter optical wave guiding structure — silica nanowires — for microphotonic devices. We briefly discussed the fabrication, geometry, and guiding properties of these wires. Using these nanowire waveguides as building blocks, we also demonstrated methods for tailoring, supporting and assembling these wire structures for device applications. We fabricated basic components including linear waveguides, waveguide bends and branch couplers. Because silica is one of the fundamental materials for photonics, the wire-assembly approach presented here can also be applied to doped wires to form active devices. Likewise, various types of nanostructured materials with suitable dielectric properties (*e.g.*, mesoporous materials[35-37]) can be used as low-index substrates. 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 microscale optical components of significantly reduced size.

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