Waveguide bends from nanometric silica wires

Limin Tong*[a,b], Jingyi Lou[c], Eric Mazur[b]
[a] State Key Laboratory of Modern Optical Instrumentation, Zhejiang University, Hangzhou 310027, China
[b] Department of Physics and Division of Engineering and Applied Sciences, Harvard University, Cambridge, MA 02138, USA
[c] State Key Laboratory of Silicon Materials, Zhejiang University, Hangzhou 310027, China

ABSTRACT

We propose to use bent silica wires with nanometric diameters to guide light as optical waveguide bend. We bend silica wires with scanning tunneling microscope probes under an optical microscope, and wire bends with bending radius smaller than 5 μm are obtained. Light from a He-Ne laser is launched into and guided through the wire bends, measured bending loss of a single bend is on the order of 1 dB. Brief introductions to the optical wave guiding and elastic bending properties of silica wires are also provided. Comparing with waveguide bends based on photonic bandgap structures, the waveguide bends from silica nanometric wires show advantages of simple structure, small overall size, easy fabrication and wide useful spectral range, which make them potentially useful in the miniaturization of photonic devices.

Keywords: waveguide bend, silica nanowire, guiding property, bending loss, microphotonics, elastic bend.

1. INTRODUCTION

The rapidly developing micro- and nano-technology in microelectronics and photonics, together with the demand for improved performance, wider applications, and higher integration density has spurred the effort for the miniaturization of photonic devices. Reducing the size of the optical waveguide bend to a subwavelength or nanometric feature size is one of the principal steps to provide opportunities for the miniaturization of photonic devices or modules. However, due to the ultrahigh-precision requirements, fabrication of low-loss optical waveguide with subwavelength- or nanometric diameter or width, is proved to be difficult with conventional methods such as EUV- and E-beam lithography[1-3]. Also, existed nanometric waveguide structures such as surface plasmon waveguide present high optical loss[4-6], which limits their applications in photonic devices.

In a recent work[7], we showed that nanometric silica wire fabricated by a two-step taper-drawing method presents excellent diameter uniformity and atomic-level sidewall smoothness. Low-loss optical wave guiding was also experimentally observed and measured. As silica is one of the fundamental photonic materials, with these low-loss guiding wires, a series of photonic devices with nanometric feature sizes can be developed. Here we investigate the guiding properties, bending methods and potential applications of waveguide bends from these wires. At the beginning of this paper, we make a brief review of optical guiding properties of straight wires. Secondly, we introduce a method to make nanometric wire bends through micromanipulations. The fabrication, geometry and flexibility of these wire structures are investigated. We then send light into these wire bends to experimentally investigate their guiding properties. Optical losses of two wire bends are obtained. Comparing with existed waveguide bends such as photonic bandgap structures, the waveguide bends from silica nanometric wires show a number of advantages such as simple structure, small size, low loss, easy fabrication and wide useful spectral range, which make them potentially useful in future submicrometer- or nanometer-scale photonic devices.

*phytong@zju.edu.cn; phone 86 571 87951688; fax 86 571 87951358

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2. BRIEF REVIEW OF OPTICAL WAVE GUIDING PROPERTIES OF SILICA WIRE WAVEGUIDES

The geometric shape of a silica wire waveguide can be viewed as an ideal cylinder, which is similar to that of a silica fiber used for optical communication. However, because of the diameter of the wire is smaller than the wavelength, and the index difference between the silica core and air cladding (about 0.5) is much larger than that of a standard fiber (e.g. less than 0.05), typical mathematic methods used for optical fibers such as scalar wave approximation or ray optics can not be applied to the thin wire. Precise description of the guiding properties of this kind of waveguide can be obtained from the exact solutions of the Helmholtz equations (vector wave equations). The details of the guiding properties of the subwavelength-diameter wire waveguides have been reported else where[8]. Here we give a brief review of optical wave guiding properties of a straight wire, which may be helpful to get a better understanding of the behavior of waveguide bends from silica wires.

A mathematic model of an air-clad silica wire waveguide is shown in Fig.1. With assumptions that the wire waveguide has a step-index profile with a core index of fused silica (e.g. 1.46 at 633-nm wavelength) and clad index of air (1.0 at the spectral range we concerned). Propagation constants of the guided modes can be obtained from the eigenvalue equations associated with Helmholtz equations[8,9]. The single-mode condition is obtained as $V<2.405$, where $V= k\cdot D\,(n_1^2-n_2^2)^{1/2}/2$, $k=2\pi/\lambda$, n_1 and n_2 are refractive indices of silica and air respectively, D is the diameter of the wire, and λ is the wavelength of the light in air. Critical diameters for single-mode operation of silica wires at typical wavelengths are listed in Table.1. Taking into account of the dispersion of silica at a broad spectral range, D_{SM} presents a slight deviation from the linear dependence of the wavelength. The electromagnetic fields of the supported modes can be obtained by substituting the propagation constants into the exact solutions of the Helmholtz equations. For reference, electric fields at radial direction of fundamental modes (HE_{11} modes) of silica wires at 633-nm wavelength are shown in Fig.2. It shows that, for a wire thicker than e.g. 400 nm, the field is strongly confined inside the wire core, which is helpful to get low optical loss when light is guided along the bend of such a wire. The energy flow propagated around the wire is characterized by the axial component of the Poynting vector. For reference, shown in Fig.3 are Poynting vectors (axial/Z component) of a 457-nm diameter (D_{SM} at 633-nm wavelength) and 229-nm diameter (half of the D_{SM}) wires at the wavelength of 633 nm, which shows that light energy moves out of the core when the wire diameter decreases. To get an exact measurement of the power distribution around a subwavelength-diameter silica wire, fractional power inside (or alternatively, outside) the silica core can be obtained by integrating Poynting vector within (or outside) the core area. Figure 4 gives fractional power of the fundamental mode inside the silica core at wavelengths of 633 and 1550 nm.

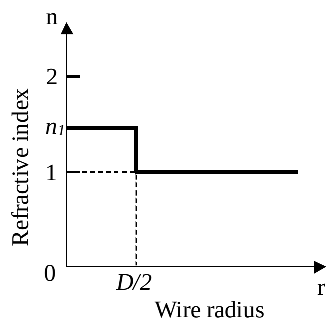

Fig.1 Mathematic model of an air-clad silica wire waveguide. n_1 stands for refractive index of the silica core, and D is the diameter of the silica wire.

It shows that the fractional power is strongly dependent on the diameter of the wire and the wavelength of the light. For example, in a thick wire at a relatively short wavelength, e.g. 800-nm diameter at 633-nm wavelength, almost all energy is confined inside the core; while in a thin wire at long wavelength, e.g. 300-nm diameter at 1550-nm wavelength, most of the energy is guided in the air. Proper selection of the wire diameter at specific wavelength is critical to get low optical loss and small size of the wire bend.

Table 1. Critical diameters for single-mode operation (D_{SM}) of silica wires at typical wavelengths

Wavelength (nm)	325	633	808	980	1310	1550
D_{SM} (nm)	230	460	590	720	960	1130

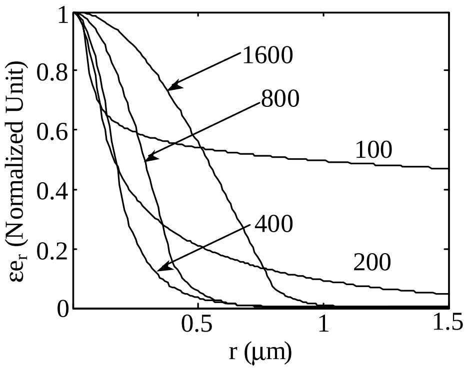

Fig.2. Radial components of electric fields of fundamental modes (*HE₁₁* modes) of silica wires at 633-nm wavelength. Wire diameters are arrowed to curves in the unit of nanometer.

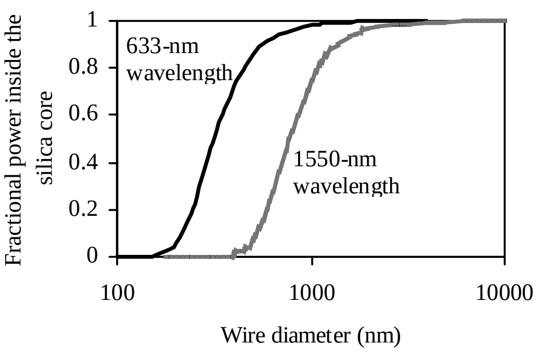

Fig.4. Fractional power of the fundamental mode inside the silica core at wavelengths of 633- and 1550 nm.

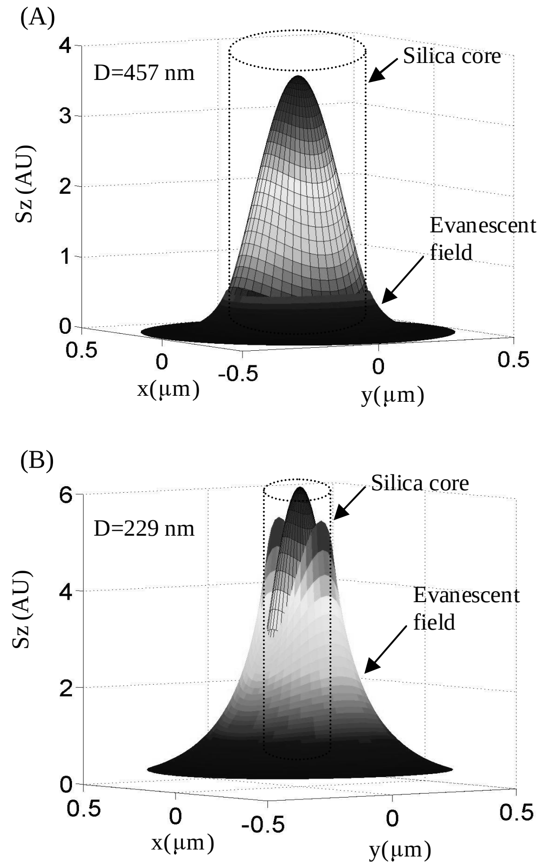

Fig.3. Z-components of the Poynting vector of (A) 457-nm and (B) 229-nm diameter wires at 633-nm wavelength.

3. BENDING OF SILICA WIRE BENDS

3.1 Elastic bending model

Before starting to bend the wire, it is necessary to investigate the mechanics of the silica wire to get properties such as strength and minimum allowable bending radius that are closely related to the bending process.

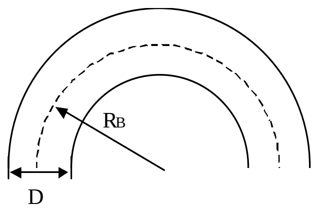

Fig.5 Bending model of a silica nanowire

The bending model is shown in Fig.5, where we assume the wire diameter to be *D*, the bending radius to be R_B. R_B is defined as the distance between the center of the bending circle and the central axis of the wire. For a cylindrical wire, the minimum allowable elastic bending radius (R_{Bm}) can be obtained as[10]

$$R_{Bm} = \frac{ED}{2\sigma}, \qquad (1)$$

where E is the Young's modulus of the wire material, σ is the tensile strength of the wire. For silica, E is found to be strain dependent and empirically given as [11]

$$E(\varepsilon) = E_0(1 + \alpha\varepsilon + \beta\varepsilon^2), \qquad (2)$$

where ε is strain, E_0 =72.2 *GPa*, is the modulus at zero strain, α=3.2, and β=8.48.

The ideal strength of silica is about 16 Gpa[12,13], but the real strengths are much lower because of various factors such as flaws of the materials and moisture in the surrounding atmosphere. Here we use optimal experimental values of 6 Gpa for silica[13], which are measured at the room temperature in air with size on the order of micrometers. Although mechanical properties are known to vary with size, reliable values with smaller sizes are not available so far.

Calculated R_{Bm} for silica wires with different diameters are shown in Fig.6. Since materials with smaller sizes usually show much higher strengths, for reference, R_{Bm} calculated with ideal strengths are also provided as dotted lines. Noting that there may be large nonlinearity of Young's modulus when tensile strength approaches ideal strength in the bending, R_{Bm} calculated from ideal strengths is only used for rough estimation. Results in Fig.6 show that, R_{Bm} increases with the increasing of wire diameter. The minimum allowable bending radius (calculated with experimental strength) is about 7.5 times of the diameter, for example, a 500-nm-diameter silica wire may be able to be bent experimentally to a radius of about 4 μm.

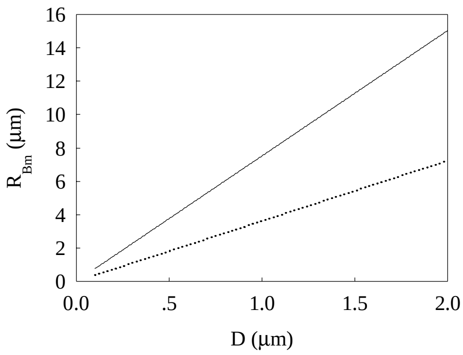

Fig.6 Minimum allowable elastic bending radii of silica wires with different diameters. Solid lines are calculated with real strengths, and dashed lines are calculated with ideal strengths.

3.2 Bending of nanmetric silica wires with micromanipulations

The system used to bend the silica wire is shown in Fig.7. We use two scanning tunneling microscope (STM) probes for manipulating the wire. STM probes are mounted on two 3-dimension micro-/nano-manipulators. A long-working-distance microscope objective with a CCD camera is used to real-time monitoring the bending process. A video clip captured from the monitor is also shown in the right of Fig.7, where a 450-nm diameter silica wire is held and bent by the two STM probes. When a proper objective and good illumination are used, it is possible to find and manipulate silica wires with

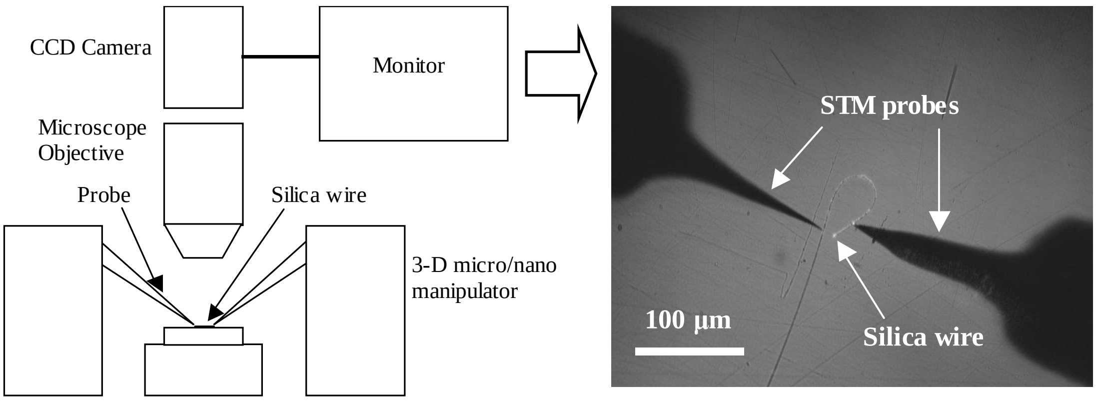

Fig.7. A schematic diagram of the micromanipulation system for bending silica wires. Shown in the right is a photo captured from the monitor, where a 450-nm diameter silica wire is held and bent by the two STM probes.

diameters below 200 nm. The bent wire can be placed on a well-polished substrate such as silicon or silica wafer. Because of the van der Waals attraction and friction between the wire and the substrate, when we remove the probes, the wire bend usually keeps the shape and attaches itself to the substrate.

Two types of wire bends are obtained by micromanipulation mentioned above. One is shown in Fig.8, in which a 260-nm-diameter wire is simply bent with a bending radius of about 4 μm. Because diameter of the wire (260 nm) is well below the wavelength of the visible light, the wire looks much thicker in optical micrograph than in SEM image due to optical diffraction. Another type is shown in Fig.9, where a 500-nm-diameter wire is tied to a 14-μm-diameter microring. The ring is firstly made with a larger diameter; we pull the two end of the wire and reduce it to the size shown in Fig.9. The wires do not break in these bends, showing that they have high mechanical strengths and flexibilities.

From Eq.(1), the tensile strength of a bent wire can be estimated as:

$$\sigma = \frac{ED}{2R_B}, \qquad (3)$$

using R_B=4 μm and D=260 nm, we obtain a strength of at least 2.5 GPa for the wire shown in Fig.8. The wires can be bent much more sharply than those shown in Fig.8 and 9. Shown in Fig.10 is a sharp bend formed with a 290-nm-diameter silica wire with a minimum bending radius of 2.7 μm, estimated strength of this wire is around 6 Gpa, which equals the highest strength that has been obtained experimentally under similar test conditions[13]. The high strength of these wires indicates that silica wires fabricated by taper drawing method have high uniformity in geometry and good integrity in structure.

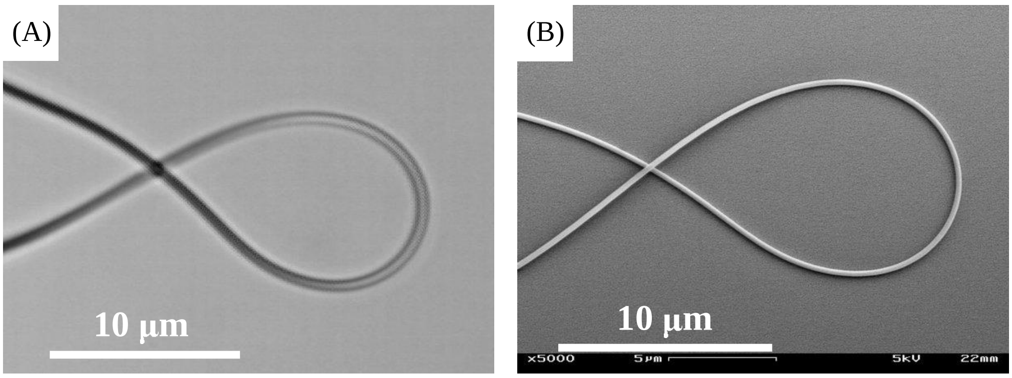

Fig.8. (A) Optical and (B) SEM micrographs of a simple bend formed with a 260-nm-diameter silica wire with a bending radius of about 4 μm. The wire is placed on a silicon wafer.

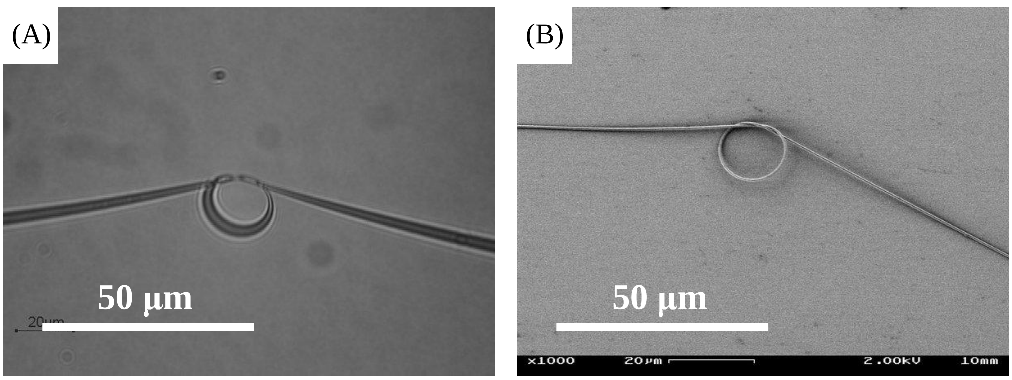

Fig.9. (A) Optical and (B) SEM micrographs of a 14-μm-diameter microring formed with a 500-nm-diameter silica wire. The wire is placed on a silicon wafer.

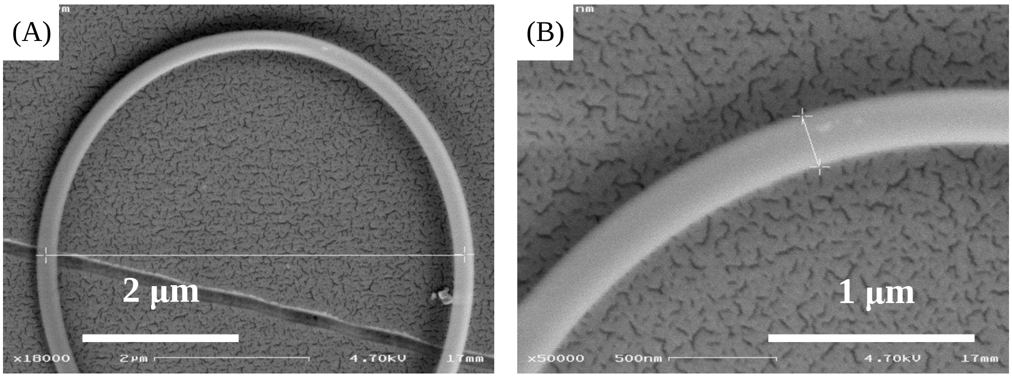

Fig.10. (A) SEM micrographs of a sharp bend formed with a 290-nm-diameter silica wire with a minimum bending radius of 2.7 µm. (B) A close-up view of a bending segment in (A).

4. OPTICAL WAVE GUIDING ALONG SILICA WIRE WAVEGUIDE BENDS

To investigate the optical wave guiding properties of the wire bends, we have tried to send a He-Ne laser (633-nm wavelength) into these wires. Shown in Fig.12 is an optical micrograph of a He-Ne light guided through a 9-µm-radius bend formed with a 500-nm-diameter silica wire, the light output at the right end of the bend can be seen clearly. Fig.13 gives an optical micrograph of a He-Ne light guided through a 25-µm-radius microring formed with a 490-nm-diameter silica wire. The homogeneous scattering along the wire before and after the microring indicates that the loss of the wire bend in the ring is very low. Measured with 633-nm-wavelengtth light, we have obtained the optical loss as low as 1.6 dB for a 6-µm-radius U-shape bend (similar to the one shown in Fig.12) with wire diameter of 500 nm; and a loss less than 1 dB for the microring shown in Fig.13. We contribute the low bending losses of these wire bend to the high uniformity of

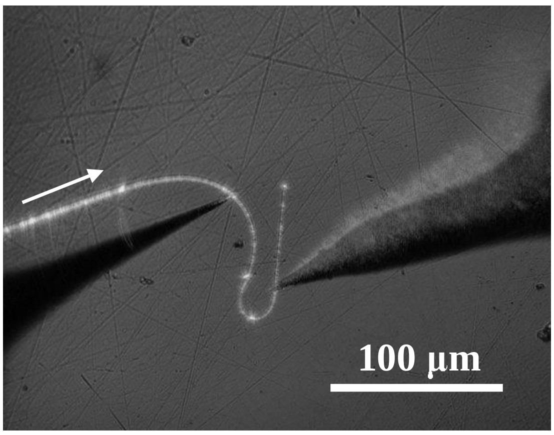

Fig.12. Optical micrograph of a He-Ne light guided through a 9-µm-radius bend formed with a 510-nm-diameter silica wire. The white arrow indicates the direction of the light propagation.

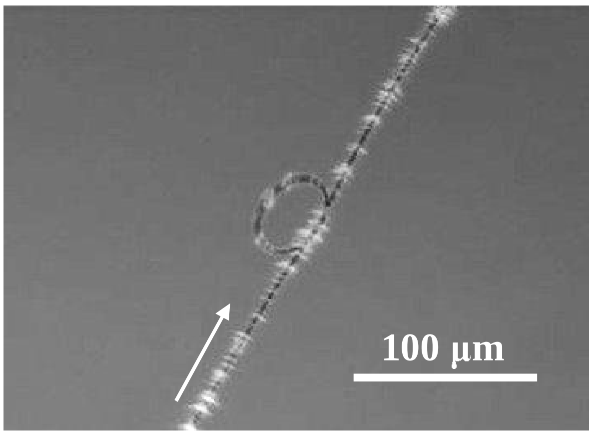

Fig.13. Optical micrograph of a He-Ne light guided through a 25-µm-radius microring formed with a 490-nm-diameter silica wire. The white arrow indicates the direction of the light propagation.

the wire, the large index difference between silica core and air, and relatively large wire diameter (note that the wire diameters we selected are slightly larger than the critical diameter for single-mode operation at 633-nm wavelength) for tight confinement of optical fields. Losses on the order of 1 dB per bend are small enough to be acceptable for many photonics devices. For comparison, waveguide bends formed with planar photonic crystal structures not only require multiple periods (which increase the overall size) and sophisticated fabrication techniques, but they also have inevitable out-of-plane loss[14-16]. In contrast, waveguide bends assembled with nanometric silica wires show the advantages of compact overall size, low optical loss, simple structure and easy fabrication[17]. Furthermore, a silica wire bend can be used to guide light from the near infrared to ultraviolet wavelengths, which can not be achieved by a photonic crystal waveguide bend.

4. CONCLUSIONS

In conclusion, we have briefly introduced the fabrication and guiding propertyies of silica wire bends. Two types of wire bends have been obtained by means of micromanipulation under an optical microscope. The wires show high mechanical strengths and flexibilities. He-Ne light has been launched into and guided through these bent structures, and low bending loss has been observed. Comparing with existed waveguide bends such as photonic bandgap structures, the waveguide bends from nanometric silica wires show advantages of simple structure, small size, low loss, easy fabrication and wide useful spectral range. Since reducing the overall size of waveguide bends is one of the principal steps in the miniaturization of microphotonic devices, wire waveguide bends proposed here are promising for using as building blocks in future submicrometer- or nanometer-scale photonic devices.

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