Submicron and nano-diameter silica wires for optical wave guiding

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ABSTRACT

Based on the exact solutions of Maxwell's equations, we have studied the basic theoretical properties of submicron and nano-diameter air-cladding silica-wire waveguides. The single-mode condition and the modal field of the fundamental modes have been obtained. Silica wires with diameters of 100-1000nm and lengths ranging from hundreds of micrometer to over 1 millimeter have been fabricated. SEM examination shows that these wires have uniform diameters and smooth surfaces, which are favorable for optical wave guiding. Light has been sent into these wires by optical coupling, and guiding light through a bent wire has also been demonstrated. These wires are promising for assembling photonic devices on a micron or submicron scale.

Keywords: Silica wire, submicron-diameter, nanowire, optical waveguide, high index-difference, Maxwell's equation, exact solution, numerical solution, microphotonics.

1. INTRODUCTION

Except for a few cases such as the fiber tapers used in near-field scanning optical microscope probing, most of the optical waveguides currently used in optical communication, sensing and integrated optics are of micron-scale or even larger. Similar to integrated circuits in the microelectronic industry, the level of integration also might be a mark of the progress of optical integrated devices[1]. Therefore, developing optical waveguides on submicron or nanometer scale may be important and necessary for advancing the research and applications of optical waveguides to a smaller scale. However, there are few reports on submicron or nanometer-diameter optical waveguides. One approach[2,3], fabricating silicon submicron strip waveguides on a silica substrate by photolithography and reactive ions etching, yields waveguides with size of 0.5μm; however, the waveguides were fixed on the substrate with a rectangular-like cross-section. Another report[4], using a nanometer-diameter metal wire to confine light energy, showed an optical loss as large as 10^4dB/mm, which is too large to be useful.

Recently, several research works on silica and semiconductor nanowires have been reported[5,6,7], they can be used as optical waveguides if they have satisfied optical qualities. Among these wires, we think that silica wire is one of the most promising materials for optical wave guiding, because silica is an excellent and important photonic material for many of the existing optical devices, and silica waveguides—the glass optical fibers—are the backbone of modern optical communications. The reduction of the size of silica waveguides may provide opportunities for reducing the size of many other photonic devices.

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Our aim in studying the basic properties of air-cladding silica waveguides with submicron or nanometer-diameters is to show the possibility of guiding optical waves by these wires. We start our theoretical research from the exact solutions of Maxwell's equations, and provide basic properties of silica-wire waveguides at typical wavelengths. We also demonstrate experimental results of sending light into and guiding light through these wires.

2. BASIC THEORY FOR AIR-CLADDING SILICA-WIRE OPTICAL WAVEGUIDES

2.1 Mathematic model

The basic model for the submicron/nanosize waveguide studied here is shown in Fig.1. The waveguide is a circular cross-section, step-index profile, infinite air-cladding nonabsorbing silica core, with 3 presumptions: (1) Core diameter is not very small (*e.g.*, >10nm), so that the electric permittivity $\varepsilon(r,\omega)$ and magnetic permeability $\mu(r,\omega)$ can be used to describe the average response of atoms/molecules of SiO_2 to the incident electromagnetic waves; (2) time-dependences of the incident light waves are in the form of $e^{-i\omega t}$, so that they have constant phase relation between each other to establish a spatial steady state; and (3) the waveguide have a length large enough to establish the spatial steady state. The index profile of such a model is expressed as

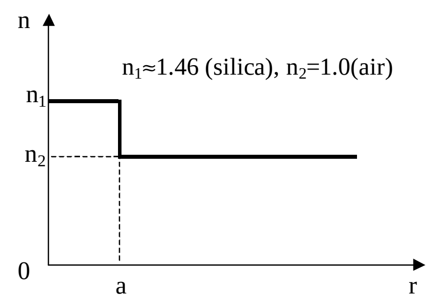

Fig.1 Mathematic model of an air-cladding silica-wire waveguide

$$n(r)=\begin{cases} n_1, & 0\le r<a; \\ n_2, & a\le r<\infty. \end{cases} \quad (1).$$

For conventional step index single mode fibers with $\Delta=(n_1^2-n_2^2)/(2n_1^2)<<1$, usually we use weakly guiding (scalar wave) approximation and Gaussian approximation to get relatively simple and accurate solutions of the guiding modes. However, for air-cladding silica nanowires with large index differences, weakly guiding approximation cannot be used, so we use exact solutions. We start from the vector wave equations for nonabsorbing and source free media as

$$\left(\nabla^2+n^2k^2-\beta^2\right)\vec{e}=0,$$
$$\left(\nabla^2+n^2k^2-\beta^2\right)\vec{h}=0. \quad (2),$$

where $k=2\pi/\lambda$.

Eigenvalue equations of Eq.(2) are [8]

$$\text{HE}_{vm}\text{ and EH}_{vm}\text{ modes}: \quad \left\{\frac{J_v'(U)}{UJ_v(U)}+\frac{K_v'(W)}{WK_v(W)}\right\}\left\{\frac{J_v'(U)}{UJ_v(U)}+\frac{n_2^2K_v'(W)}{n_1^2WK_v(W)}\right\}=\left(\frac{v\beta}{kn_1}\right)^2\left(\frac{V}{UW}\right)^4 \quad (3),$$

$$\text{TM}_{0m}\text{ modes}: \quad \frac{J_1(U)}{UJ_0(U)}+\frac{K_1(W)}{WK_0(W)}=0 \quad (4),$$

$$\text{TE}_{0m}\text{ modes}: \quad \frac{n_1^2J_1(U)}{UJ_0(U)}+\frac{n_2^2K_1(W)}{WK_0(W)}=0 \quad (5),$$

where J_v is the Bessel function of the first kind, and K_v is the modified Bessel function of the second kind, $U=a(k_0^2n_1^2-\beta^2)^{1/2}$, $W=a(\beta^2-k_0^2n_2^2)^{1/2}$, $V=k_0\cdot a\,(n_1^2-n_2^2)^{1/2}$.

Since the diameter of the wire studied here is very small, in most cases, the wire is operated as a single-mode waveguide even with a large index-difference, so we only consider the fundamental mode. Eq.(3) are used to obtain the propagation constant β of the fundamental modes (HE_{11} modes), and Eq.(4) and Eq.(5) is used to obtain the single mode condition of the waveguide.

2.2 Single-mode condition

Comparing Eq.(4) and Eq.(5) with eigenvalue equations of weakly guiding single mode fibers[9]

$$U\frac{J_{l-1}(U)}{J_l(U)} = -W\frac{K_{l-1}(W)}{K_l(W)}, \qquad l = \begin{cases} 1, & TE_{0m}, TM_{0m} \\ v+1, & EH_{vm} \\ v-1, & HE_{vm} \end{cases} \qquad (6),$$

it is obvious that they are the same for TE_{0m} modes, where TE_{01} modes determine the single mode condition. Although TM_{0m} modes have a different equation, notice that at the cutoff, W=0, TM_{01} modes still have a cutoff V-number larger than that of TE_{01} modes. So the single mode condition of the air-cladding silica-wire waveguide is the same as the standard glass fibers [8]

$$V = 2\pi\cdot\frac{a}{\lambda_0}\cdot\left(n_1^{\ 2} - n_2^{\ 2}\right)^{\frac{1}{2}} \approx 2.405 \qquad (7).$$

Some result from Eq.(7) are shown in Table.1.

Table.1 Single-mode condition for air-cladding silica wires at some typical wavelengths ($n_1=1.46$, $n_2=1.0$)

Wavelength	400nm	632.8nm	1.0μm	1.3μm	1.55μm
Maximum diameter for single-mode operation (nm)	286	452	715	930	1110

2.3 Fundamental modes

For fundamental modes(HE_{11} modes), the eigenvalue equation Eq.(3) becomes

$$\left\{\frac{J_1'(U)}{UJ_1(U)} + \frac{K_1'(W)}{WK_1(W)}\right\}\left\{\frac{J_1'(U)}{UJ_1(U)} + \frac{n_2^{\ 2}K_1'(W)}{n_1^{\ 2}WK_1(W)}\right\} = \left(\frac{\beta}{kn_1}\right)^2\left(\frac{V}{UW}\right)^4 \qquad (8).$$

No analytical solutions exist for Eq.(8), so we use the software *Mathematica* to obtain the numerical solutions of the propagation constant β . The results are shown in Fig.2. By these solutions, most properties that relate to the fundamental modes can be obtained. When expressing the electromagnetic fields as

$$\begin{cases} \vec{E}(r,\phi,z) = (e_r\hat{r} + e_\phi\hat{\phi} + e_z\hat{z})e^{i\beta z}e^{i\omega t}, \\ \vec{H}(r,\phi,z) = (h_r\hat{r} + h_\phi\hat{\phi} + h_z\hat{z})e^{i\beta z}e^{i\omega t} \end{cases} \qquad (9),$$

we then have the radial distribution of the electric fields of the fundamental modes according to Ref.(8)

$$|\bar{e}_r| \propto \left|\frac{a_1J_0(Ur/a) + a_2J_2(Ur/a)}{J_1(U)}\right|, \quad 0 < r < a,$$

$$|\bar{e}_r| \propto \left|\frac{U}{W}\frac{a_1K_0(Wr/a) - a_2K_2(Wr/a)}{K_1(W)}\right|, a < r < \infty. \qquad (10).$$

Radial fields(plotted as $D=\varepsilon E$) of silica-wire waveguides at the wavelength of 632.8nm with radii of *a=100nm, 300nm, 700nm* from Eq.(10) and the numerical solutions of β are depicted in Fig.3 . For reference, a standard Gaussian profile is also provided. It is obvious that the air-cladding silica-wire waveguides have tighter confinement than the Gaussian profile, which is a good approximation for modal fields of standard single-mode fibers. When the wire radius is larger than 300nm, the confinement increases along with the decreasing of wire diameter, which is favorable for confining light energy inside a smaller volume. Further decreasing the radius, *e.g.*, to *a*=100nm in Fig.3, the tail of the profile rises, indicating that the field begins to distribute to a farther distance with a considerable intensity. The modal field distribution may be a useful reference for selecting waveguide parameters for different applications. For example, in high-density optical integration, a tight confinement may be required. In other applications based on optical coupling, a weak confinement is usually beneficial to obtaining high coupling efficiency within a short interaction length. In addition, it is also a good start for obtaining many other properties such as waveguide dispersion of air-cladding silica-wire waveguides.

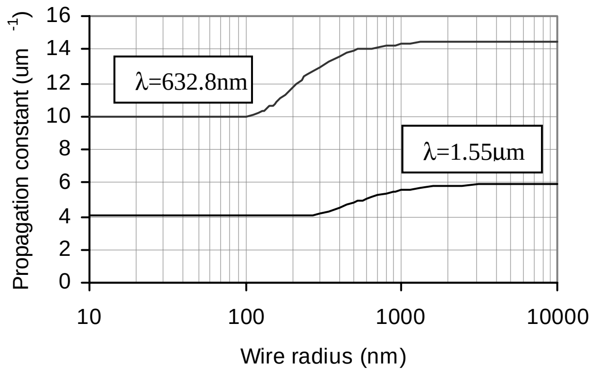

Fig.2. Numerical solutions of propagation constant β of the fundamental modes at the wavelength of 632.8nm and 1.55μm

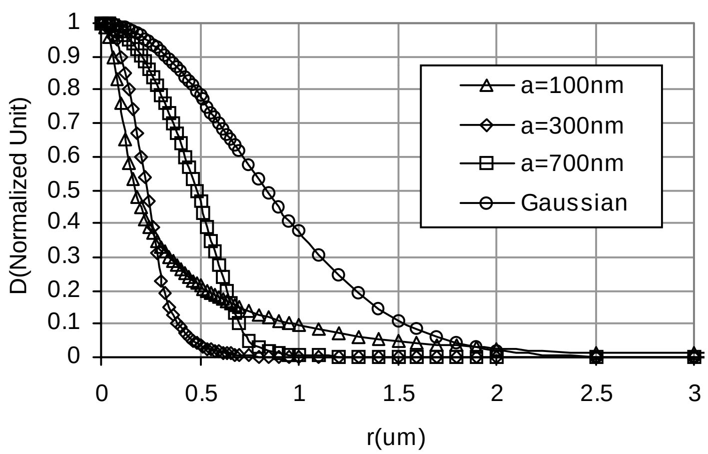

Fig.3. Modal fields($D=\varepsilon E$) of silica-wire waveguides with radii of *a=100nm, 300nm, 700nm*. A Gaussian distribution is provided for reference, the wavelength is 632.8nm.

3. EXPERIMENTAL DETAILS

3.1 Appearances of submicron and nano-diameter silica wires

We have obtained silica wires with diameters ranging from 100nm to 1000nm by a recently developed method[10]. Comparing with silica wires obtained by a Gallium catalyzed VLS method[5], silica submicron or nanowires we obtained have much larger lengths. Depending on the fabrication conditions, the length of these wires range from hundreds of micrometers to over 1 millimeter. They also have uniform diameters and smooth surfaces, which is beneficial for obtaining low optical losses.

Typical SEM images of silica wires we obtained are shown in Fig.4, Fig.5, and Fig.6. All the samples are deposited by a thin (thickness<10nm) layer of gold before SEM examination for electron conducting. In Fig.4, a 120nm-diameter wire(left) rests on a 470nm-diameter wire(right), a wire with length >200μm and diameter smaller than 200nm is difficult to be individually handled. Then both wires are placed on a standard aluminum SEM stub. From the image, we can see that, even under a high magnification(×100000 in Fig.4), the surfaces of the both wires are very smooth. For comparison, smooth surfaces are difficult to obtain with submicron optical waveguides fabricated by photolithography. Fig.5 shows a suspending 400nm-diameter wire with a very uniform diameter, in the examination, the two ends of the wire are fixed on conducting tapes (one of the tape edges is shown in the right of Fig.5) on the aluminum stub. In the left, the wire is some hundreds of microns away from the aluminum surface, a measured average diameter fluctuation factor $\Delta D/\Delta L$ (ΔD is the diameter variation and ΔL the length to be counted) is better than 0.1% over a length of about 300μm. Fig.6 shows a long silica wire with diameter of about 500nm. The total length of the wire is about 1 millimeter, which is long enough for both optical characterizations and applications.

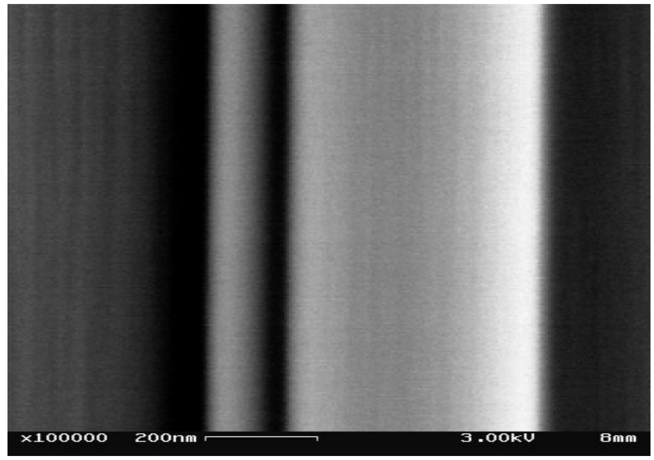

Fig.4. A 120nm-diameter silica wire(left) rests on a 470nm-diameter wire(right). Both wires are then placed on a standard aluminum SEM stub and deposited by a thin layer of gold.

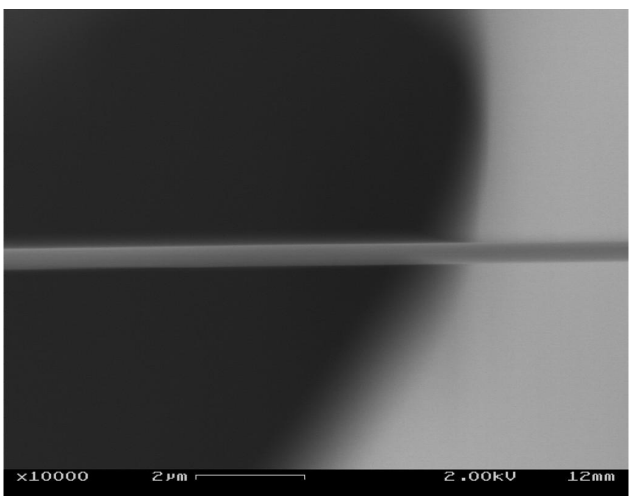

Fig.5. A suspending 400nm-diameter silica wire with a uniform diameter.

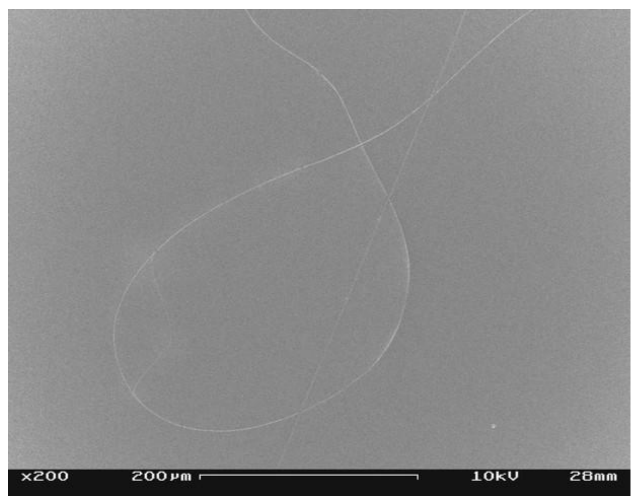

Fig.6. A 500nm-diameter silica wire with a length of about 1 millimeter.

3.2 Guiding light by submicron and nano-diameter silica wires

We have successfully guided light by the submicron and nano-diameter silica wires described above. The light was sent into the wire by optical coupling as shown in Fig.7. The incident light is first sent into a fiber taper with a submicron diameter end(right), and then the light is coupled into the silica wire(left) that is placed in parallel and contact with the taper end. In Fig.7, the silica wire is 500nm in diameter, and the taper end is about 550nm in diameter, the overlap of the taper and the wire can be seen in the Fig.7A when there is no incident light. When the laser is turned on, a relatively large scattering at the overlap can be seen in Fig.7B. The scattering intensity in the 500nm-diameter wire indicates that a considerable amount of the light energy has been transmitted from the taper to the wire.

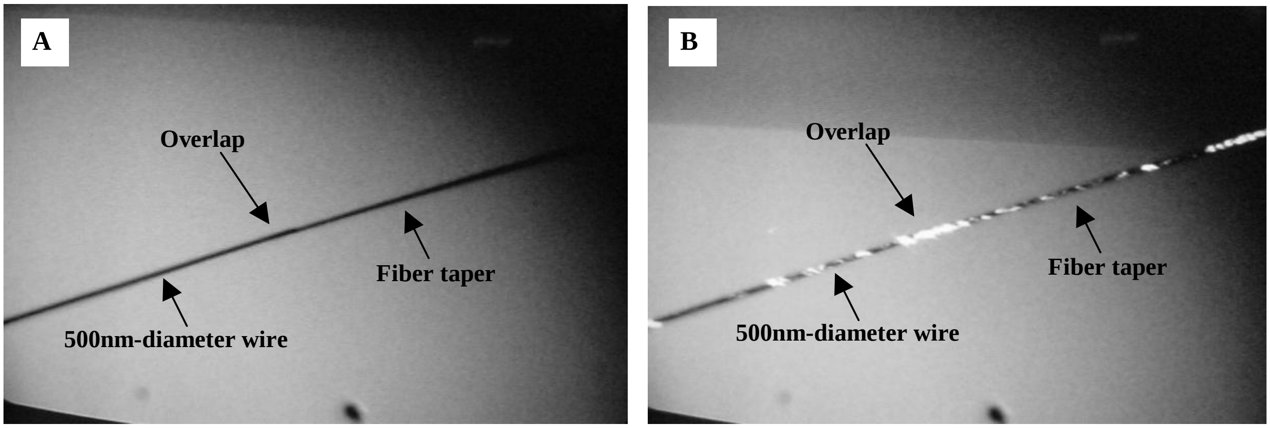

Fig.7 Coupling light into a 500nm-diameter silica wire by a 550nm-diameter taper end. The photos are taken by a CCD camera (COHU, INC.) with a microscope objective, and the light used is a He-Ne laser at wavelength of 632.8nm. (A) The laser is turned off, (B)the laser is turned on.

In the experiments, we have also successfully guided light through a sharply bent silica wire. As shown in Fig.8, a 570nm-diameter silica wire was bent to a 3-dimensional curve, the incident light from a 1500nm-diameter taper end was coupled into the wire and guided though the bend with a minimum bending radius of about 150μm. All the photos in Fig.7 and Fig.8 are taken by a CCD camera(COHU, INC.) with a microscope objective, and a He-Ne laser light source operated at the wavelength of 632.8nm. The ability to send light into and guide light through submicron diameter silica wires makes it possible to measure optical properties of these wires, as well as test optical devices assembled by these wires. Additionally, the ability to guide light through bends with very small diameter will be useful in making photonic devices in smaller sizes, which is one of our goals in the study submicron and nanometer-diameter silica wires.

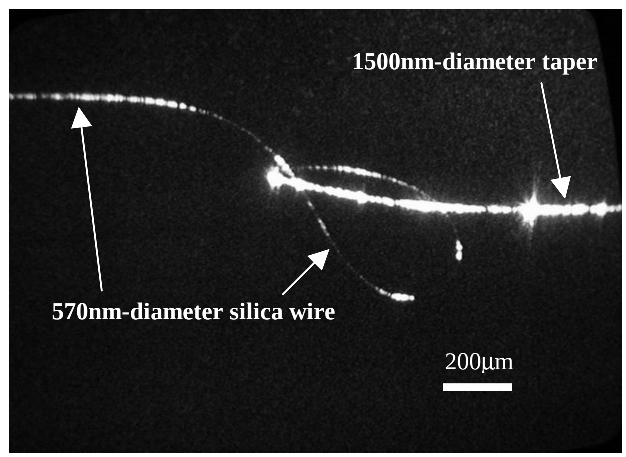

Fig.8. Guiding light through a 3-dimension bend of 570nm-diameter silica wire. The photo is taken by a CCD camera (COHU, INC.) with a microscope objective, the light used is a He-Ne laser at wavelength of 632.8nm.

4. CONCLUSIONS

So far, we have theoretically studied basic properties of air-cladding silica-wire waveguides based on exact solutions of Maxwell's equations. The single-mode condition and the modal field of the fundamental modes have been obtained, which are a basis for further study of many other properties of the high index-difference silica-wire waveguides. Silica wires with diameters of 100-1000nm and length up to 1 millimeter have been fabricated. SEM examinations show that these wires have uniform diameters and smooth surfaces, which is favorable for low-loss optical guiding. Light has been sent into these wires by optical coupling through fiber tapers. Guiding light through a 150μm-radius bend is also demonstrated. Primary theoretical and experimental results indicate that, silica wires with submicron or nanometer-diameters may be used to guide optical wave on a smaller scale comparing with the conventional micron-scale waveguides in integrated optics or standard glass fibers in optical communications. We believe that, these wires are promising for many applications including optical sensing, optical communication, nonlinear optics and near-field optics. Further work covering theoretical simulations, optical characterizations and device applications of these wires is in progress.

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