Dispersion Properties of Silicon and Silica Photonic Nanowires for Nonlinear Applications

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***Abstract*—Dispersion properties of air-clad and silica-coated silicon photonic wires for nonlinear applications are investigated with exact solutions of Maxwell's equations. We show that the GVD of silicon nanowires can be tailored for different wavelengths in the infrared region of the spectrum. In comparison, air-clad silica tapered fibers require diameters of several micrometers in order to extend the zero dispersion points to the infrared wavelengths. By immersing silica wires in liquid we can obtain a minimum and flat GVD region in the infrared.**

I. Introduction

In the past, dielectric optical waveguides with widths or diameters from micrometers to millimeters have been used for applications in many fields such as optical communication, optical sensing and optical power delivery systems. Photonic device applications benefit from minimizing the width of the waveguides, but fabricating low-loss optical waveguides with subwavelength diameters remains challenging because of high precision requirement. Recently, several types of dielectric wires of optical qualities have been obtained. These wires are much thinner than the commonly used waveguides. They can be used as wire-waveguides with subwavelength-diameter cores and building blocks in the future micro- and nano-photonic devices. Due to their small sizes, photonic wires can have tight optical confinement and large effective nonlinearities. In addition, the dispersion of these nano-waveguides can be engineered by changing the core diameter, allowing for positive, negative, and zero dispersion operation. Wires with tailored dispersion can be used for a variety of photonic applications including supercontinuum generation and soliton-effect compression [1]. Photonic wires can be made from different dielectrics such as silica and silicon [2, 3]. Silicon has a larger nonlinear refractive index [4] compared to silica, which gives a higher nonlinear coefficient and relatively lower energies are required for nonlinear applications [5-9].

Tapered fibers with diameters down to several micrometers have been shown to be useful in supercontinuum generation. Tapered silica fibers with air and liquid claddings have been studied. The zero dispersion points of these tapered fibers determine the region of spectral broadening and white light generation. An important mechanism responsible for spectral broadening in these fibers is soliton splitting, which occurs near the zero dispersion points and in the region of anomalous GVD. In many applications, we may require a large and homogeneous broadening of the spectrum. The characteristics of the anomalous GVD and higher-order dispersions determine the shape and bandwidth of the broadened spectrum. A large and slowly varying anomalous GVD or positive dispersion parameter along with small higher-order dispersions are ideally needed for soliton-effect compression of optical pulses. By adjusting the core diameter of the fiber and choosing appropriate materials for the fiber core and cladding, the zero dispersion points occur at the desired wavelengths and supercontinuum can be generated in a specified spectral range. In order to obtain a broadened spectrum to the largest extent, we require a nearly flat GVD in the anomalous dispersion region with slow variation. It is very difficult to realize such a design in the case of tapered fibers. For example, extending the spectral broadening region and the zero dispersion points to the infrared wavelengths of the spectrum from 1.2 μm to 1.8 μm requires tapered silica fibers with diameters of several micrometers. Therefore, using such a thick fiber will result in much lower light intensities and reduced nonlinearity in nonlinear optics applications where a large nonlinear coefficient is desired. It may be possible to use the second zero dispersion point of thinner fibers or photonic nanowires made of a silica core and with air cladding. However, we are not able to obtain a region of large and nearly flat anomalous GVD in the infrared wavelengths from 1.2 μm to 1.8

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μm and it is also more difficult to fabricate these air-clad nanowires.

In this paper, based on exact solutions of Maxwell's equations and numerical calculations, we study dispersion properties of silicon and silica photonic wires and examine their GVD and higher-order dispersions in the infrared spectral range. We consider both air-clad and silica-coated silicon nanowires. We also consider a silica tapered fiber immersed in acetonitrile and show that it is possible to obtain a region of anomalous GVD with slow variation and very small higher-order dispersions.

II. METHODOLOGY

Regardless of γ, Because dispersion is considered, we have equation (1):

$$\begin{cases} T \equiv t - \frac{z}{vg} \\ i\frac{\partial A}{\partial z} = -i\frac{\alpha}{2}A + \frac{\beta_2}{2!}\frac{\partial^2 A}{\partial T^2} - \gamma|A|^2 A \\ L_D \equiv \textit{Dispersion Length} \\ L_{NL} \equiv \textit{Non Linear Length} \\ \frac{t-\left(\frac{z}{vg}\right)}{T_0} = \frac{T}{T_0} \\ A(z,\tau) = \sqrt{P_0}\, e^{-\frac{\alpha}{2}z} u(z,\tau) \\ i\frac{\partial u}{\partial z} = \frac{\operatorname{sgn}(\beta_2)}{2L_D}\frac{\partial^2 u}{\partial z^2} - \frac{e^{-\alpha z}}{L_{NL}}|u|^2 u \\ L_D \equiv \frac{T_0^2}{|\beta_2|} \quad L_{NL} \equiv \frac{1}{\gamma P_0} \\ L \ll L_{NL} \textit{ and } L \gg L_D \end{cases} \tag{1}$$

Then we can calculate GVD. If $\gamma = 0$, in (2):

$$\begin{cases} i\frac{\partial u}{\partial z} = \frac{1}{2}\beta_2\frac{\partial^2 u}{\partial T^2} \\ \tilde{U}(z,w) = F[u(z,\tau)] \\ U(z,\tau) = \frac{1}{2\pi}\int_{-\infty}^{\infty}\tilde{U}(z,w)e^{-\omega i\tau}d\tau \\ i\frac{\partial\tilde{U}(z,w)}{\partial z} = -\frac{1}{2}\beta_2\omega^2\tilde{U}(z,w) \\ i\frac{\partial\tilde{U}(z,w)}{\partial z} = -\frac{1}{2}\beta_2\omega^2\tilde{U}(z,w) \\ \frac{d\tilde{U}(z,w)}{\tilde{U}} = i\frac{\beta_2}{2!}\omega^2 d\tau \\ \tilde{U}(z,w) = U(0,w)e^{i\frac{\beta_2}{2}\omega^2 z} \\ \begin{cases} U(z,\tau) = \frac{1}{2\pi}\int_{-\infty}^{\infty}\tilde{U}(0,w)e^{i\frac{\beta_2}{2}\omega^2 z}dw \\ \tilde{U}(0,w) = \int_{-\infty}^{\infty}u(0,\tau)e^{-\omega i\tau}d\tau \end{cases} \end{cases} \tag{2}$$

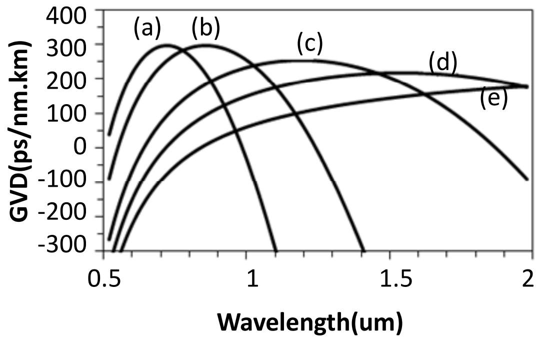

Figure 1. Dispersion of a silica tapered fiber with air cladding as a function of wavelength for core diameters of (a) 0.8 μm, (b) 1 μm, (c) 1.5 μm, (d) 2 μm, and (e) 3 μm

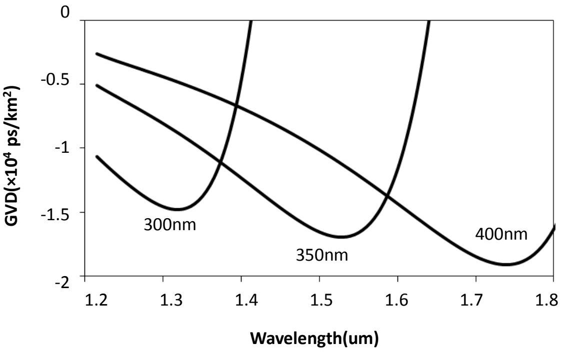

Figure 2. GVD of an air-clad silicon nanowire as a function of wavelength for different core diameters

III. RESULTS

We show the dispersion curves of a fused silica tapered fiber with air cladding for different diameters in Figure 1. The wavelength dependent refractive index of silica was used to calculate the dispersion curves. A region of anomalous GVD is obtained in the infrared with values in the order of -250 ps^2/km, for core diameters exceeding 1.5 μm. The first zero dispersion points exceed a wavelength of 800 nm for core diameters larger than 3 μm. This is caused by the large difference between the refractive indices of fused silica and air, and limits the position and the bandwidth of the broadened spectrum due to spectral broadening.

GVD of air-clad and silica-clad silicon wires are shown in Figures 2 and 3. It shows that, dispersions of these wire-waveguides can be very large compared to conventional fibers. For example, dispersion of a 400 nm diameter silicon wire at 1.55 μm wavelength is -3220 ps^2/km. The dispersion of a 350 nm air-clad silicon wire at a wavelength of 1.55 μm is -1680 ps^2/km. These values are much larger than those of the material dispersion.

The total dispersion (combined material and waveguide dispersions) of a wire-waveguide can be made zero, positive, or negative when a proper diameter is chosen. Therefore, these wires present opportunities for achieving enhanced dispersions with reduced sizes in many fields such as optical communication and nonlinear optics.

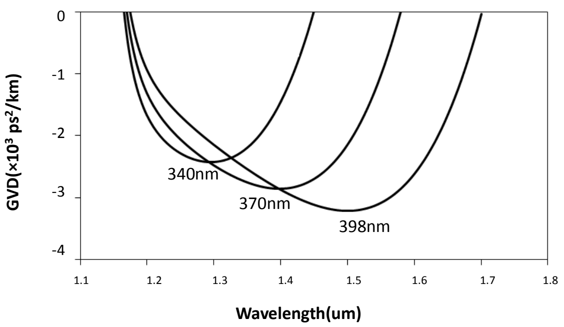

Figure 3. GVD of a silica-clad silicon nanowire as a function of wavelength for different core diameters

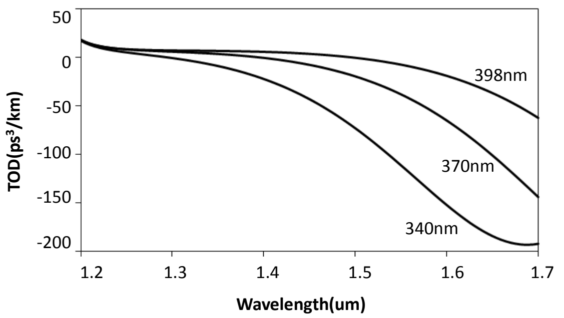

Figure 4. TOD of a silicon nanowire with silica cladding as a function of wavelength for different core diameters

In order to achieve spectral broadening and supercontinuum generation in the infrared wavelengths of the spectrum and to extend the broadened bandwidth, we should use materials with a smaller difference between their refractive indices. As seen in these figures, there is a minimum and nearly flat region of anomalous GVD, which in the silica-clad silicon nanowire is flatter and more symmetrical compared to the air-clad silicon nanowire. Therefore, we expect that the higher-order dispersions of the silica-coated silicon nanowire to be smaller than those for the air-clad silicon nanowire. It can also be seen that for a silica-clad silicon nanowire both zero dispersion points are located in the infrared region of the spectrum around the 1.55 μm wavelength. This makes a silica-coated silicon wire more suitable for nonlinear applications such as supercontinuum generation and soliton-effect pulse compression.

In Figure 4, the TOD of the silica-coated silicon nanowire has been plotted as a function of wavelength for the same core diameters. We can see that in the same region of wavelengths where there is a minimum and nearly flat anomalous GVD, the nanowire has a small TOD which is ideally needed for the soliton-effect compression of optical pulses.

Values of the GVD, TOD, fourth-order dispersion, and fifth-order dispersion have been compared in Table 1 for the two silicon nanowires. We can see that the silica-clad silicon nanowire has much smaller higher-order dispersions compared to the air-clad silicon nanowire. The fact that, at a wavelength of 1.5 μm, the ratio of higher-order dispersions to the GVD is much smaller for a silica-clad silicon nanowire, makes it more suitable for different nonlinear application, in particular, soliton-effect pulse compression.

In Figure 5, we have plotted the GVD of an air-clad silica wire as a function of wavelength in the infrared region of the spectrum for two different core diameters. As seen in Figure 5, there is a region of minimum and negative GVD at a wavelength of 1.5 μm for a core diameter of 1.584 μm. However, the first zero dispersion point is still far from the infrared spectral range and the GVD curve is not symmetrical. To have both dispersion points in the infrared region and obtain a more symmetrical GVD

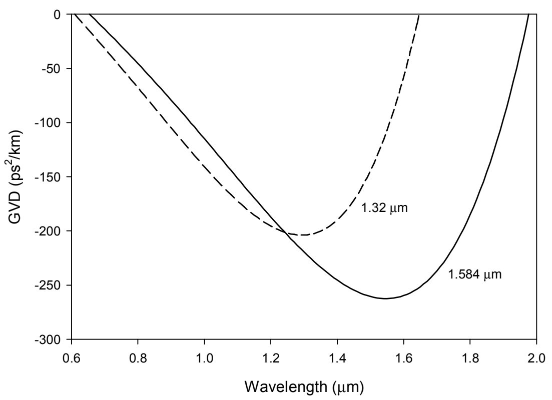

Figure 5. GVD of an air-clad silica wire as a function of wavelength for two different diameters

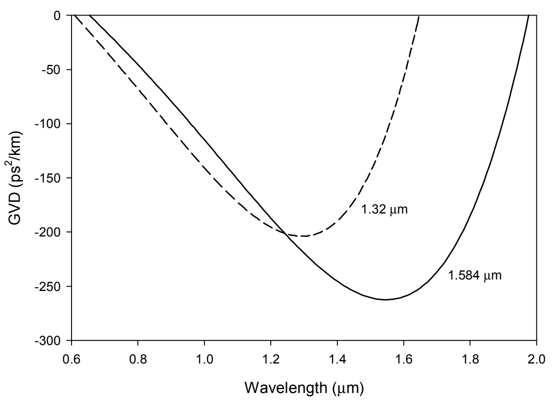

Figure 6. GVD of a silica wire immersed in acetonitrile as a function of wavelength for two different core diameters

curve and, hence, smaller higher-order dispersion, we can immerse a silica tapered fiber in a liquid such as acetonitrile. In the near infrared region of the spectrum and at the important wavelengths of 1300 nm and 1550 nm water has high losses, which is due to the O-H bond vibration overtones. Therefore,

Table 1. Comparison of GVD and higher-order dispersions for silicon nanowires

Nanowire	GVD (ps^2/km)	TOD (ps^3/km)	Fourth (ps^4/km)	Fifth (ps^5/km)
Silica-clad (398nm)	-3218	0.0141	0.1284	-0.0020
Air-clad (344nm)	-16721	3.578	1.716	-0.0565

We propose to use silica wires immersed in acetonitrile in the infrared spectral range. Acetonitrile does not have O-H vibrational overtone absorption lines in the near infrared and is almost transparent in this spectral range. Acetonitrile can transmit about %99 of the light traveling through it at wavelengths of 1300 nm and 1550 nm of the spectrum. The GVD of a silica tapered fiber immersed in acetonitrile is shown in Figure 6, which is more symmetrical compared to the GVD of an air-clad silica wire and leads to smaller higher-order dispersion. Higher-order dispersions of a silica tapered fiber with air and acetonitrile claddings at a wavelength of 1.55 um. The air-clad silica tapered fiber has a diameter of 1.584 µm and the silica tapered fiber immersed in acetonitrile has a diameter of 3.052 µm. It can also be seen that both zero dispersion points are now located in the infrared region of the spectrum around the 1.55 µm wavelength. This makes a silica wire immersed in acetonitrile more suitable for nonlinear applications of super continuum generation and soliton-effect pulse compression.

IV. CONCLUSIONS

We studied dispersion properties of silicon and silica wires for nonlinear applications of supercontinuum generation and soliton-effect pulse compression. We showed that, the GVD of silicon nanowires can be tailored for different wavelengths in the infrared region of the spectrum. GVD of a silica-clad silicon wire is flatter and more symmetrical compared to the air-clad silicon nanowire and, hence, has smaller higher-order dispersions. Moreover, both zero dispersion points are moved to the infrared region of the spectrum around the 1.55 µm wavelength, for the silica-coated silicon wire. In comparison, silica tapered fibers require diameters of several micrometers in order to extend the zero dispersion points to the infrared wavelengths. For an air-clad silica wire, we can only move one of the zero dispersion points to the infrared region of the spectrum. We showed that by immersing a silica wire in acetonitrile, we can locate both zero dispersion points in the infrared region of the spectrum and obtain a more symmetrical GVD and smaller higher-order dispersions.

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