Compact and Tunable Slow and Fast Light Device Based on Two Coupled Dissimilar Optical Nanowires

Lei Shi, Xianfeng Chen, Liang Xing, and Wei Tan

***Abstract*—We propose a novel and compact all-optical device for tunable slow and fast light propagation in parallel coupled structures consisting of two dissimilar optical nanowires. Advancement/delay tunability is achieved by varying the spacing between two nanowires. We develop a simplified analytical model to describe the dependence of achievable time advancement/delay and pulse broadening on the diameter of optical nanowires and it is indicated that this model agrees well with numerical results. Simulation results show that achievable maximum group-index change is about 1.4 and a 10-mm-long device can advance/delay a 2-ps pulse by 15.9 ps with pulse broadening factor equaling to 2.**

***Index Terms*—Optical delay lines, optical fiber devices, optical fiber dispersion, propagation.**

I. Introduction

TECHNIQUES of controlling the group velocity of a light pulse propagation in optical materials are very significant for their important applications in all-optical signal processing [1], [2], such as data synchronization, variable optical delay lines, and optical switching. Corresponding techniques include electromagnetically induced transparency (EIT) [3], [4], coherent population oscillations (CPO) [5], [6], stimulated scattering (stimulated Brillouin scattering (SBS) and stimulated Raman scattering (SRS)) [7]–[10], optical parametric amplification (OPA) [11], [12], wavelength conversion combining fiber dispersion (WCCFD) [13], coupled-resonator-induced transparency (CRIT) [14]–[16], photonic crystal-based resonance structures [17], [18], and other schemes [19]. However, these works have respective limitations, e.g., extreme condition (extremely cold or hot gases) for EIT, large pulsewidth (ms) for CPO, narrow bandwidth (tens of MHz) and small temporal delay (1 bit period) for SBS, large bandwidth but small temporal delay (smaller than SBS) for SRS, dependent on single mode sources at very long wavelength (out of the 1.55-μm window) and relatively small temporal delay for OPA, large temporal delay but a complicated hybrid system for WCCFD, highly compact size but likewise small temporal delay for CRIT, and tunable only by heating (not all-optical tunable) for photonic crystal-based resonance structures.

Recently optical nanowire-based photonic devices have attracted much attention [20]–[27] for their wide applications due to their large nonlinear coefficient, strong evanescent field, and superiority in fabrication, manipulation and integration [28]–[36]. In this paper we propose a novel compact and tunable slow and fast light device based on asymmetric parallel coupled structures consisting of two dissimilar optical nanowires. For two dissimilar nanowires have strongly different dispersion behavior the supermodes in the coupled structure may exhibit giant group velocity dispersion (GVD), and consequently generate considerable group-index change corresponding to the group indexes of guided modes in individual optical nanowires. Advantages of the proposed device are: 1) highly compact; 2) simple configuration; 3) suited to advance/delay ps and sub-ps pulses; 4) capable of achieving relatively large time advancement/delay; 5) needless to change the signal wavelength and bandwidth; and 6) capable of generating time advancement/delay at any common transparent wavelength of SiO_2 and Si materials. We numerically and analytically study the evolution of group indexes and GVD of the supermodes with the tunable parameter-the spacing between two nanowires and the optimized parameter-the diameter of two nanowires and the input pulse width, and the results show that a 10-mm-long device can advance/delay a 2-ps pulse by 15.9 ps with pulse broadening factor equaling to 2.

II. Device Principle

A. Supermode Theory

A parallel coupled structure consisting of two dissimilar optical nanowires with uniform diameters is shown in Fig. 1(a). Here we choose silica (SiO_2) and silicon (Si) as typical nanowire materials [37]–[41] for our simulations, and the coupled structure is placed in a homogeneous medium. The coupling of two individual modes generates two supermodes, β_e is the propagation constant of even supermodes, and β_o is the propagation constant of odd supermodes. They are given by [42]

$$\begin{aligned}\beta_{e/o} &= \bar{\beta} \pm \sqrt{\delta^2+\kappa^2}\\ \bar{\beta} &= \frac{\beta_1+\beta_2}{2}\\ \delta &= \frac{\beta_1-\beta_2}{2}\\ \kappa &= \sqrt{\kappa_{12}\kappa_{21}}\end{aligned} \tag{1}$$

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The authors are with the Department of Physics, Shanghai Jiao Tong University, Shanghai 200240, China (e-mail: lshi129@yahoo.com.cn; xfchen@sjtu.edu.cn).

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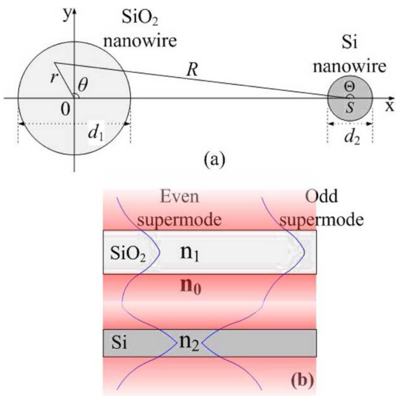

Fig. 1. (a) Cross section of a parallel coupled structure. (b) Two supermodes in the parallel coupled structure. d_1 and d_2 are the diameters of SiO_2 nanowires and Si nanowires, respectively. S is the spacing between SiO_2 and Si nanowires.

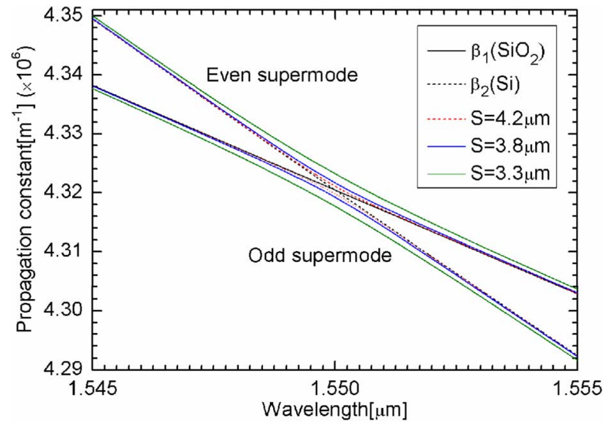

Fig. 2. Propagation constants of individual guided modes (black lines) and the supermodes (colored lines) for three different spacings. The diameter of SiO_2 and Si nanowires used for the simulation are 729 and 277 nm, respectively.

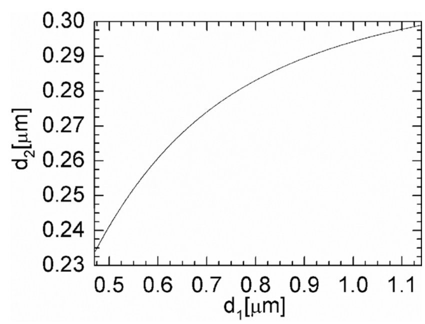

Fig. 3. Diameter of Si nanowires versus the diameter of SiO_2 nanowires, which make phase-matching hold at $\lambda_0 = 1.55\ \mu$m.

where β_1, β_2 are the propagation constant of the individual guided modes in SiO_2 nanowires and Si nanowires, respectively, and κ_{12}, κ_{21} are the mode coupling coefficients. Equation (1) is also applicable to pulsed light propagation in the coupled structure when the device length L is satisfied with $L \ll L_{D1,2}$, where $L_{D1,2}$ is the dispersion length of nanowaveguides 1 and 2, respectively.

For asymmetric coupled structures κ_{12} and κ_{21} can be derived strictly [43].

B. Tunable Slow and Fast Light in Parallel Coupled Structures Consisting of Two Dissimilar Optical Nanowires

According to $v_g = -(2\pi c/\lambda^2)(d\lambda/d\beta)$ [44], group indexes of individual guided modes and the supermodes are given by

$$n_{g1,2} = \frac{c}{v_{g1,2}} = -\frac{\lambda^2}{2\pi}\frac{d\beta_{1,2}}{d\lambda} \tag{2a}$$

$$n_{ge/o} = \frac{c}{v_{ge/o}} = -\frac{\lambda^2}{2\pi}\frac{d\beta_{e/o}}{d\lambda} \tag{2b}$$

where $n_{g1,2}$ and $v_{g1,2}$ correspond to group indexes and group velocities of individual guided modes 1 and 2, respectively, and $n_{ge/o}$, $v_{ge/o}$ correspond to group indexes and group velocities of the even supermode and the odd supermode, respectively.

For the parallel coupled structures consisting of two dissimilar optical nanowires, of which individual guided modes have strongly different dispersion behavior $\beta_{1,2}(\lambda)$, the phase-matching may holds at a certain wavelength λ_0, $\beta_1(\lambda_0) = \beta_2(\lambda_0)$. The strongest coupling effect happens at λ_0, and we call λ_0 the resonant wavelength. Wavelength-dependent propagation constants of individual guided modes and the supermodes are shown in Fig. 2. Note that two supermodes may generate large GVD, namely considerable group-index variation.

The time advancement/delay ΔT for a light pulse passing through a material with propagation length L can be written as [2]

$$\Delta T = \frac{L}{c} \cdot \Delta n_g(\lambda_c) \tag{3}$$

where $\Delta n_g(\lambda_c)$ is the group-index change at the center wavelength λ_c. Based on the group-index change generated by the supermodes we can obtain slow and fast light propagation by adjusting light propagation into the coupled structure, and tune the achievable time advancement/delay by varying the spacing between SiO_2 and Si nanowires in real time.

III. Numerical Results

All numerical results displayed in following figures are obtained by an exact solution of eigenvalue equation for the coupled structure with ambient refractive index $n_0 = 1$.

A. Diameters of Optical Nanowires for Phase Matching

We suppose that phase-matching holds at $\lambda_0 = 1.55\ \mu$m and investigate the optical nanowires which are satisfied with the condition for single-mode operation. At the wavelength of 1.55 μm corresponding critical diameters of SiO_2 and Si nanowires for single-mode operation are 1139 and 356 nm, respectively. For a given SiO_2 nanowire, only the Si nanowire with a specified diameter can make phase-matching hold at the appointed resonant wavelength. The corresponding relation between the diameter of SiO_2 nanowires and Si nanowires is shown in Fig. 3, where d_1, d_2 are the diameters of SiO_2 and Si nanowires, respectively.

In following simulations we refer to calculate the evolution of several key parameters (including group indices, GVD of the supermodes, generated group-index change, pulse broadening, and time advancement/delay) with the transverse size of the device, namely the diameter of optical nanowires which constitute the coupled structure. For each couple of diameters of SiO_2 and

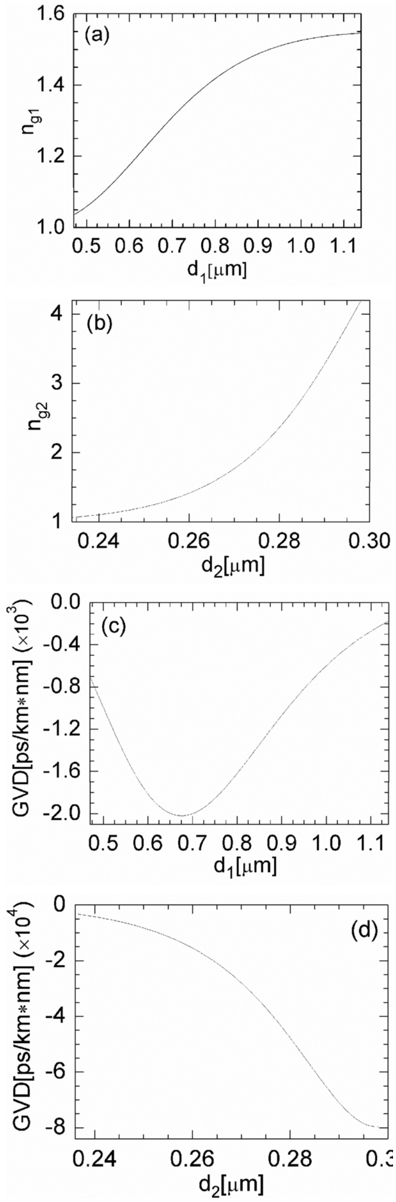

Fig. 4. (a), (b) Group indexes of the individual guided modes. (c), (d) GVD of the individual guided modes.

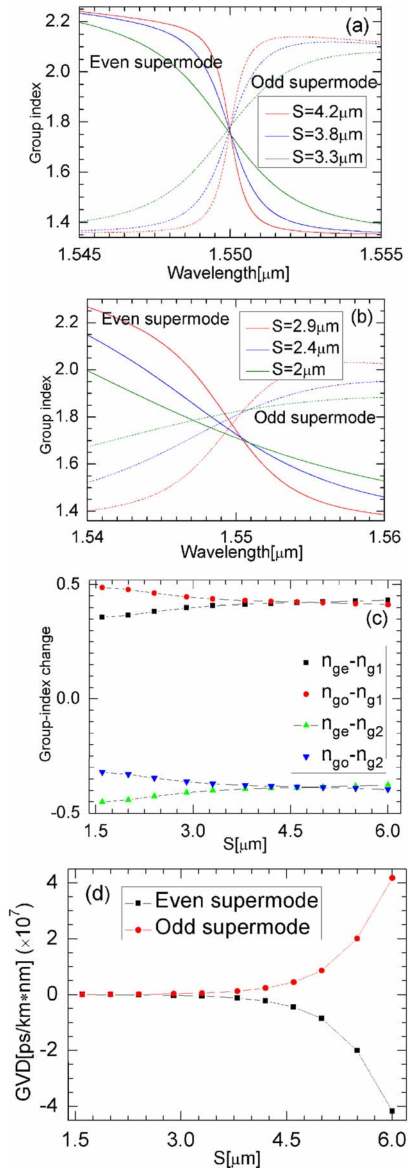

Fig. 5. (a), (b)Wavelength-dependent group indexes of the supermodes for six different spacings. (c) Group-index change versus the spacing. (d) GVD of the supermodes versus the spacing.

Si nanowires used in our calculations the phase matching should be satisfied and from Fig. 3 it is clear that there is a one-to-one correspondence between the diameter of SiO_2 and Si nanowires, accordingly we choose the diameter of SiO_2 nanowires to characterize the transverse size of the device in our simulations.

B. Group indexes and GVD of Individual Guided Modes

The group index of individual guided modes is defined as (3), and GVD of individual guided modes is given by [44]

$$D_{1,2} = \frac{d}{d\lambda}\left(\frac{1}{v_{g1,2}}\right). \tag{4}$$

We can obtain diameter-dependent $n_{g1,2}$ and $D_{1,2}$ at the resonant wavelength $\lambda_0 = 1.55$ μm, and the results are shown in Fig. 4. Results in Fig. 4(a)–(b) show that both n_{g1} and n_{g2} increase with the diameter of optical nanowires respectively, and there is a large group index difference between them. Results in Fig. 4(c)–(d) show that both diameter-dependent D_1 and D_2 are normal dispersion, and $D_1 \ll D_2$.

C. Group indexes and GVD of Two Supermodes

First we consider the effect of the spacing S between SiO_2 nanowires and Si nanowires on group indexes and GVD of two supermodes. The diameter of SiO_2 and Si nanowires are fixed at 729 and 277 nm, respectively. Results in Fig. 5(a) and (b) show the wavelength-dependent group indexes of two supermodes for six different spacings. As the spacing gets smaller the curves of wavelength-dependent group indexes get gentler. We pay attention to group indexes of the supermodes at the resonant wavelength $\lambda_0 = 1.55$ μm, and from Fig. 5(c) we know that the group indexes of two supermodes at the resonant wavelength are higher than the group index of individual modes in SiO_2 nanowires and lower than the group index of individual modes in Si nanowires. It is clear that we can tune the group-index changes generated by two supermodes at resonant wavelength by varying the spacing. The tuning range of group-index variations is about ± 0.08 corresponding to the tuning range of $S = 4.4\ \mu$m for the given device size. However, the evolution tendencies of group-index change generated by two supermodes with the spacing S are opposite. GVD of the supermodes is given by

$$D_{e/o} = \frac{d}{d\lambda}\left(\frac{1}{v_{ge/o}}\right). \tag{5}$$

Results in Fig. 5(d) show that $D_e(\lambda_0)$ and $D_o(\lambda_0)$ are normal and anomalous dispersion respectively, and both $D_e(\lambda_0)$ and $D_o(\lambda_0)$ increase with the spacing. From Fig. 5(c)–(d) it is indicated that for slow light propagation when the odd supermode is excited the smaller spacing corresponds to the smaller dispersion and larger group-index change, and for fast light propagation when the even supermode is excited the smaller spacing corresponds to the smaller dispersion and larger group-index change. That is, excitation of the odd supermode can achieve optimum performance for slow light, and excitation of the even supermode can achieve optimum performance for fast light.

Then, we investigate the effect of the diameter of SiO_2 and Si nanowires on group indexes and GVD of the supermodes. When the spacing S is fixed at 2.5 μm, the results are shown in Fig. 6. Fig. 6(a) and (b) show the evolution of wavelength-dependent group indexes of two supermodes with the diameter of optical nanowires. With the diameter of optical nanowires getting small the curves of wavelength-dependent group indexes get gentle. We pay attention to group indexes at the resonant wavelength $\lambda_0 = 1.55\ \mu$m, and it is shown in Fig. 6(c) that corresponding to the individual modes guided in SiO_2 nanowires two supermodes generate slow light propagation and corresponding to the individual modes guided in Si nanowires two supermodes generate fast light propagation. The evolution tendencies of diameter-dependent group indexes of two supermodes are nearly the same, and the smaller diameter corresponds to the smaller group-index change. Finally as to GVD results in Fig. 6(d) show that the sign of $D_e(\lambda_0)$ and $D_o(\lambda_0)$ are opposite, and both $D_e(\lambda_0)$ and $D_o(\lambda_0)$ increase with the diameter of optical nanowires.

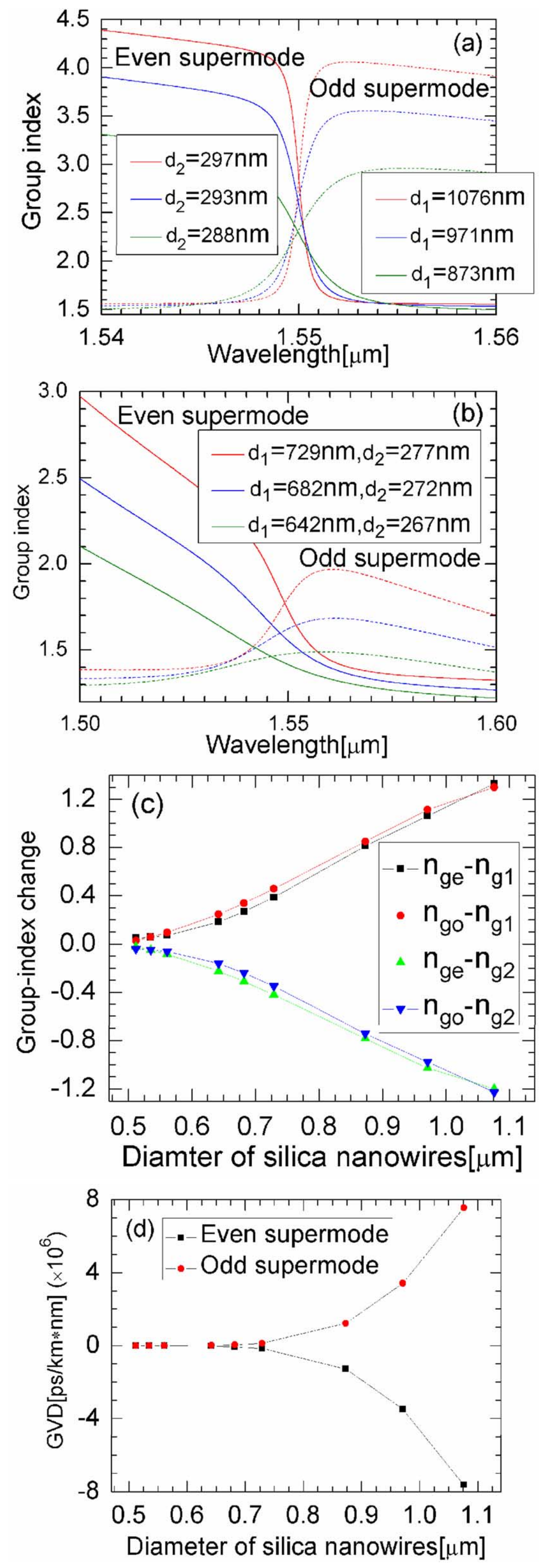

Fig. 6. (a), (b) Wavelength-dependent group indexes of two supermodes for coupled structures with different diameters. (c) Generated group-index change versus the diameter of optical nanowires. (d) GVD of two supermodes versus the diameter of optical nanowires.

IV. Prediction of the Time Advancement/Delay and Pulse Broadening

A. Analytical Model of Group indexes and GVD of the Supermodes

Here, we develop a simplified analytical model to calculate the evolution of the time advancement/delay with the diameter of optical nanowires that constitute the coupled structure.

We ignore the dependence of κ on the wavelength, and, at the resonant wavelength λ_0, we obtain

$$n_{ge/o}(\lambda_0) = -\frac{\lambda_0^2}{2\pi}\left(\frac{d\beta_{e/o}(\lambda)}{d\lambda}\right)_{\lambda=\lambda_0} \tag{6a}$$

$$\rightarrow n_{ge}(\lambda_0) \cong n_{go}(\lambda_0) \cong \frac{1}{2}\left(n_{g1}(\lambda_0) + n_{g2}(\lambda_0)\right)$$

$$\begin{aligned}\Delta n_{g1}(\lambda_0) &= n_{ge/o}(\lambda_0) - n_{g1}(\lambda_0)\\ &\cong \frac{1}{2}\left(n_{g2}(\lambda_0) - n_{g1}(\lambda_0)\right) > 0\end{aligned} \tag{6b}$$

$$\begin{aligned}\Delta n_{g2}(\lambda_0) &= n_{ge/o}(\lambda_0) - n_{g2}(\lambda_0)\\ &\cong \frac{1}{2}\left(n_{g1}(\lambda_0) - n_{g2}(\lambda_0)\right) < 0.\end{aligned} \tag{6c}$$

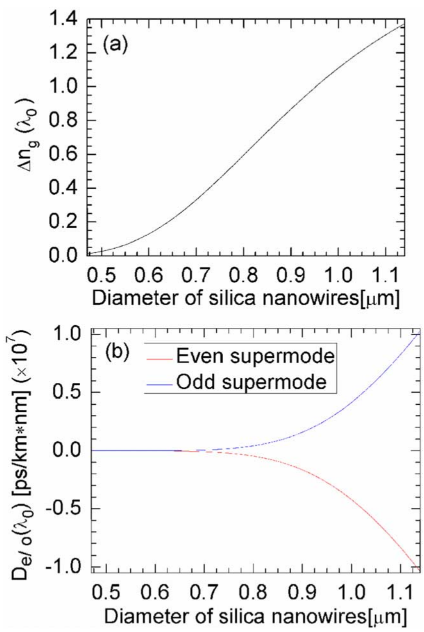

Fig. 7. (a) Group-index change of the supermodes versus the diameter of optical nanowires. (b) Absolute value of GVD of the supermodes versus the diameter of optical nanowires.

We define $\Delta n_g(\lambda_0) = |\Delta n_{g1}(\lambda_0)| = |\Delta n_{g2}(\lambda_0)|$, and the diameter-dependent $\Delta n_g(\lambda_0)$ is shown in Fig. 7(a). The result shows that $\Delta n_g(\lambda_0)$ increases monotonically with the diameter of optical nanowires, and, compared with the numerical result shown in Fig. 6(d), the resulting $\Delta n_g(\lambda_0)$ is comparative exact.

Based on the same assumption GVD of the supermodes has the form

$$D_{e/o}(\lambda_0) = \frac{D_1(\lambda_0) + D_2(\lambda_0)}{2} + \Delta D_{e/o}(\lambda_0) \tag{7a}$$

where

$$\Delta D_{e/o}(\lambda_0) \cong \mp \frac{\pi c}{2\lambda_0^2 \kappa}\left(\frac{1}{v_{g1}(\lambda_0)} - \frac{1}{v_{g2}(\lambda_0)}\right)^2. \tag{7b}$$

From Fig. 4(c) and (d) and (8), we can obtain the diameter-dependent total dispersion $D_{e/o}(\lambda_0)$ and the results are shown in Fig. 7(b). It is shown that $D_e(\lambda_0)$ and $D_o(\lambda_0)$ are normal and anomalous dispersion respectively, and both $D_e(\lambda_0)$ and $D_o(\lambda_0)$ increase monotonically with the diameter of optical nanowires. Compared with Fig. 6(e) it is indicated that the resulting $D_{e/o}(\lambda_0)$ agrees with the numerical result very well.

As mentioned above, the simplified analytical model for $\Delta n_g(\lambda_0)$ and $D_{e/o}(\lambda_0)$ we develop here is effective enough.

B. Simulation of the Time Advancement/Delay and Pulse Broadening

Achievable time advancement/delay ΔT is defined as (4), and the pulse broadening factor for the Gauss pulse is given by [42]

$$\frac{\tau_L}{\tau_0} = \left[1 + \left(\frac{2\ln 2}{\pi c}\cdot\frac{D_{e/o}(\lambda_0)L\lambda_0^2}{\tau_0^2}\right)^2\right]^{1/2} \tag{8}$$

where τ_L and τ_0 are the full-width at half-maximum (FWHM) of the input pulse and output pulse, respectively. From Figs. 5(d), 6(d), and 7(b), it is clear that

$$|D_e(\lambda_0)| \cong |D_o(\lambda_0)| \tag{9}$$

and we use $D_o(\lambda_0)$ for our calculations.

SiO_2 nanowires with length up to ~ 10 cm and uniform diameter have been fabricated [23], [24], [26], [27], but available Si nanowires based on existing fabrication techniques with maximum length up to 2 cm and uniform diameter [39] are not so long as SiO_2 nanowires. Accordingly, for $\tau_0 = 2$ ps, we set the device length $L = 1$, 2, 5, and 10 mm, and for $\tau_0 = 0.5$ ps we set the device length $L = 100$, 200, 500, and 1000 μm in order that L is satisfied with $L \ll L_{D1,2}$. Then based on the results in above section we can calculate achievable time advancement/delay and corresponding pulse broadening.

If pulse broadening is relatively too large after transmission of the input pulse through the device the time advancement/delay is insignificant. Here, we choose $\tau_L/\tau_0 = 2$ as the limitation for propagation of the input pulse through the device. In consideration of the limitation, we calculate the corresponding achievable ΔT, and the results are shown in Fig. 8. For $\tau_0 = 2$ ps corresponding to four different device lengths the achievable ΔT is 3.1, 5.1, 9.8, and 15.9 ps, respectively. For $\tau_0 = 0.5$ ps corresponding to four different device lengths, the achievable ΔT is 0.27, 0.45, 0.85, and 1.38 ps, respectively.

From Fig. 8(a)–(d), it is indicated that, for a given device length (e.g., $L = 1$ mm) and pulse broadening factor, the ratio of the time advancement/delay to the input pulse width-$\Delta T/\tau_0$ is dependent on the input pulse width, and this dependence relation is shown in Fig. 8(e). We find that, for $L = 1$ mm and $\tau_L/\tau_0 = 2$, the narrower the pulse is, the larger corresponding advancement (delay)-to-pulse-width ratio is.

When the device is fabricated for practical applications, the device length L should be equal to an even multiple of coupling length $L_c = \pi/2\kappa(\lambda_0)$ in order to make the resonant center wavelength export from the input optical nanowire.

V. Discussion and Conclusion

There are still a few challenges for this scheme we propose here. One issue is that this scheme requires the diameter of SiO_2 and Si nanowires could be controlled exactly enough to make the resonant wavelength equal to the specified center wavelength. If the diameter of fabricated nanowires deviates from the theoretical value or the resonant wavelength needs to be shifted we may change the ambient refractive index or waveguide structure [37], [45] to make the phase-matching hold at the appointed center wavelength. Another issue is the tuning range of temporal advancement/delay is relatively small. When the nonlinearity should be considered we can tune the temporal advancement/delay all-optically.

The consequent subject which deserves researchers' efforts (common to all slow and fast light systems) is how to obtain larger time advancement/delay. For this scheme due to the limitation of fabrication technologies of optical nanowires on the device length achievable maximum time advancement/delay

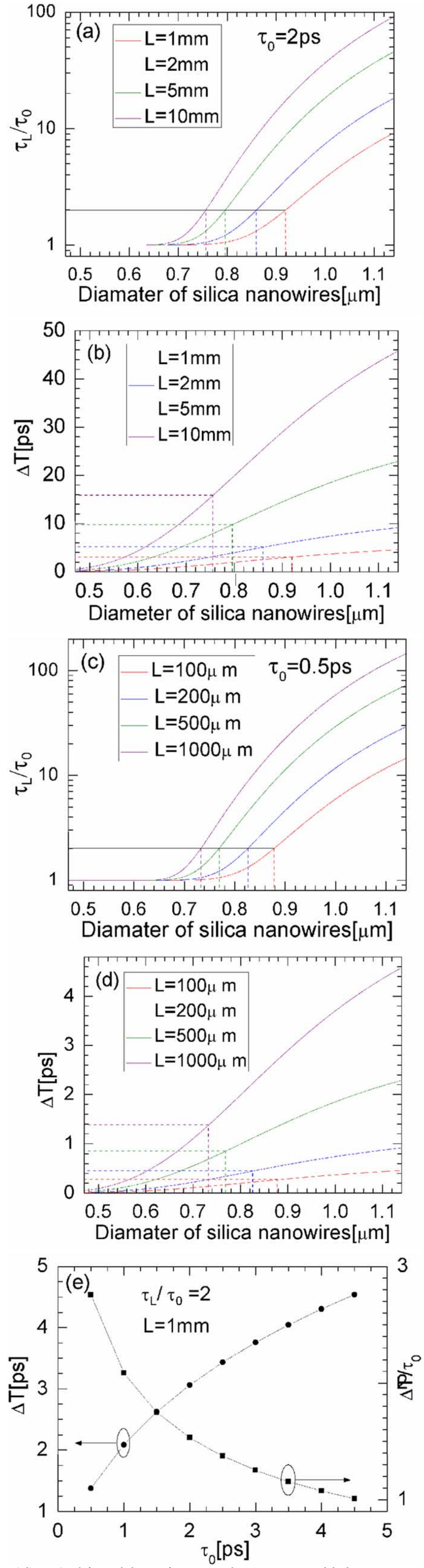

Fig. 8. (a)–(d) Achievable time advancement/delay corresponding a fixed broadening factor $\tau_L/\tau_0 = 2$ versus the diameter of optical nanowires. (e) Dependence of the time advancement/delay and advancement(delay)-to-pulse-width ratio on the input pulsewidth for a given device length and pulse broadening factor.

is restricted. Recently, Sazio *et al.* demonstrated a novel fabrication technology of semiconductor nanowires and nanotubes [46], and, to date, the longest nanotubes with length up to 30 cm have been fabricated. It may provide a way to obtain longer Si nanowires. An alternative scheme can be based on the silicon-on-insulator (SOI) platform [47] in consideration of the mature fabrication technology of longer Si nanowaveguides. The coupled structure consisting of a free-standing SiO_2 nanowire and a SOI channel nanowaveguide may also provide tunable slow and fast light propagation. Moreover, in this paper we only consider the coupling between fundamental modes of optical nanowires with single-mode operation, and the coupling between high-order modes of optical nanowires with multi-mode operation may provide larger time advancement/delay.

In summary, we have presented a novel scheme based on parallel coupled structures consisting of two dissimilar optical nanowires for tunable slow and fast light propagation. We can tune the achievable time advancement/delay by varying the spacing between two nanowires and can obtain relatively large time advancement/delay. A simple analytical model is developed to describe its physical mechanism and it is useful to design the device for optimum performance. Compared with existing techniques for achieving tunable slow and fast light this scheme has several unique advantages, and it is significant for the development of nano-scale all-optical signal processing devices.

APPENDIX

We can use a mode selector to excite the desired supermode. The mode selector is also a parallel coupled structure which is connected to our device. We can fabricate the mode selector by changing the diameter of one waveguide of our device and remain the diameter of the other waveguide of the device unchanged. We set $A_1(z)$ and $A_2(z)$ as the mode field amplitudes in the individual waveguides constituting the mode selector, and we get

$$\begin{aligned} A_1(z) = \Bigg[& \left(\cos(\varphi z) + j\frac{\delta}{\varphi}\sin(\varphi z)\right) A_1(0) \\ & - j\frac{\kappa}{\varphi}\sin(\varphi z) A_2(0)\Bigg] \exp(-j\delta z) \\ A_2(z) = \Bigg[& \left(\cos(\varphi z) - j\frac{\delta}{\varphi}\sin(\varphi z)\right) A_2(0) \\ & - j\frac{\kappa}{\varphi}\sin(\varphi z) A_1(0)\Bigg] \exp(j\delta z) \end{aligned}$$

where $\varphi = \sqrt{\kappa^2 + \delta^2}$, $\delta = (\beta_2 - \beta_1/2)$, $\kappa = \sqrt{\kappa_{12}\kappa_{21}}$. We set $A_1(0) = 1$, $A_2(0) = 0$, and the length of the mode selector is L_s. Then at L_s we have

$$\begin{aligned} A_1(L_s) &= \left(\cos(\varphi L_s) + j\frac{\delta}{\varphi}\sin(\varphi L_s)\right) \exp(-j\delta L_s) \\ A_2(L_s) &= -j\frac{\kappa}{\varphi}\sin(\varphi L_s)\exp(j\delta L_s). \end{aligned}$$

The even supermode could be excited corresponding to $A_1(L_s) = A_2(L_s)$, and the odd supermode could be excited corresponding to $A_1(L_s) = A_2(L_s)$. When the corresponding condition in the mode selector is satisfied we can make the desired supemode propagate in the device.

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Lei Shi was born in Hubei, China, on December 9, 1981. He is currently working toward the Ph.D. degree at Shanghai Jiao Tong University, Shanghai, China.

His research interest is nanophotonics.

Xianfeng Chen received the Ph.D. degree in optics from Shanghai Jiao Tong University, Shanghai, China, in 1999.

He is currently a Professor of optics with the Department of Physics, Shanghai Jiao Tong University. He has published more than 100 refereed journal articles. His research interests include nonlinear optics, ultrafast optics and nanophotonics, particularly quasi-phase-matching nonlinear optics, photonics, and devices based on magnetic micro- and submicrofibers, and quantum dots.

Xing Liang , photograph and biography not available at the time of publication.

Wei Tan , photograph and biography not available at the time of publication.