Ultrashort Pulse Propagation and Compression in Dispersion Increasing Silicon Nanowire Waveguides

Chi-Houn Lin, Shang-Da Yang , Wei-Chao Chiu, Ming-Chang M. Lee
Institute of Photonics Technologies, National Tsing Hua University, Hsinchu, Taiwan

Abstract: Ultrashort pulse propagation through silicon nanowire with longitudinally increasing normal dispersion is found (in theory) to be able to produce a broad spectrum without sidelobe, which is attractive for low-power, high-quality, stable pulse compression.
Keywords: silicon photonics, ultrafast optics, self-phase modulation, group-velocity dispersion

Introduction :
Silicon photonic nanowire waveguides [1] are attracting increasing attention during the last few years because the high index contrast between silicon core and surrounding air/oxide cladding permits tight optical confinement and significant enhancement of nonlinear optical effects. This is detrimental in terms of optical signal realy, but could be useful in some applications such as Raman laser [2], supercontinuoum generation [3,4], all-optical regeneration [5], and pulse compression [4]. As far as pulse compression is concerned, high peak intensity is desired to induce strong self-phase modulation (SPM) and spectral broadening. As a result, one would expect to operate at either zero group velocity dispersion (ZGVD) or anomalous dispersion (soliton) regime such that peak intensity remains strong as the pulse propagates through the waveguide. However, it has been shown that third-order dispersion (TOD) [4,6] and modulation instability [3,4] in these regimes would cause spectral asymmetry, fine strucure, and fluctuation, seriously degrading the shape and repeatibiluty of output pulses. Employment of dispersion decreasing fiber (DDF) improves the spectral stability and/or bandwidth broadening, but is subject to timing jitter problem [3,7]. In this study, we consider ultrashort pulse propagation through a silicon nanowire with small but longitudinally increasing normal dispersion value. It is found that the proposed dispersion changing waveguide (DCW) can provide similar pulse compression ratio as ZGVD waveguide. Besides, the ouput spectrum of DCW is well-behaved (permitting sidelobe-free transform-limited pulse), and is less sensitive to the waveguide length or input power. It should be also immune to modulation instability for most of the frequency components are ketp away from the anomalous dispersion regime. The required dispersion variation can be engineered by waveguide gemoetry [8], which is controlled by photolithographic mask and fabrication processes. Consequently, DCW is promising in compressing ultrashort pulses arisig from weak femtosecond oscillators.

2. Theory :
Pulse spectrum will get broadened while temporal pulse shape remains intact as it propagates through a nondispersive medium [$\beta_i \equiv \beta^{(i)}(\omega_0)=0$, β and ω_0 are the propagation constant and central angular freuqncy of the pulse, respectively]. Significant pulse compression can be achieved if the chirped output pulse is dispersion compensated. In the presence of TOD ($\beta_3 \neq 0$), however, frequency components at spectral wings will experience normal and anomalous dispersion even we operate at ZGVD ($\beta_2=0$). This will result in both complicated spectral shape and modulation instability due to a noticeable portion of power lies in anomalous dispersion regime [4]. To mitigate these problmes while avoiding temporal stretchng and reduction of SPM, we propose to use an adiabatic waveguide with small but longitudinally increasing normal dispersion ($\beta_2>0$). As the pulse spectrum is broadened by SPM, one has to gradually increase the β_2 value such that most optical power lies within normal dispersion regime [Fig. 1]. By properly choosing the rate of increase of β_2, interplay between SPM and weak normal dispersion will result in broad and well-behaved spectrum, which is essential for producing pedestal-free transform-limited pulse by dispersion compensation.

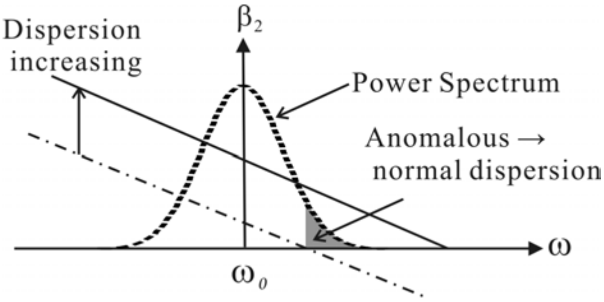

Fig. 1. Schemetic of dispersion changing waveguide.

Note that pulse propagation in dispersion decreasing or incresing structure has been extensively investigated [7,9], but premiarily limited to the cases with chaning anomalous dispersion value. Parital cancellation of opposite signs of pulse chirp induced by SPM and anomalous GVD permits soliton pulse compression and stronger spectral broadening at the cost of increased pedestal and suseptability to input pulse fluctuation [4].

3. Simulation :
The pulse propagtion behavior is modeled by the nonlinear Schrödinger-equation [6,10]:

$$i\left(\frac{\partial\psi}{\partial z}+\frac{c\kappa}{2nv_g}\alpha\psi\right)=\frac{\beta_2}{2}\frac{\partial^2\psi}{\partial\tau^2}+i\frac{\beta_3}{6}\frac{\partial^3\psi}{\partial\tau^3}+\frac{1}{2}\frac{3\omega\Gamma_1 P}{\varepsilon_0 A_0 v_g^2}(1+ir)|\psi|^2\psi$$

where ψ is the normalized amplitude, $\tau = t - z/v_g$ is the time of a frame moving with group velocity v_g, c is light speed in vacuum, κ is the confinement parameter, n is the refractive index, α is the linear absorption parameter, $\Gamma = \Gamma_1 + i\Gamma_2$ stands for the nonlinear parameter [Γ_1 and Γ_2 are related to SPM and two-photon absorption (TPA), respectively], $r = \Gamma_2/\Gamma_1$ [10], P is the peak power of input pulse, A_0 is the waveguide transverse area. TPA-induced free-carrier effect is not considered in this model.

We consider a 1550-nm, 125-fs (intensity FWHM) transform-limited Gaussian pulse sent into a 360-nm×220-nm silicon-on-insulator rectangular waveguide analyzed in [6], from which $c\kappa/(2nv_g)=0.5$, $\alpha=3.5$ dB/cm, $r=0.1$, $\gamma=3\omega\Gamma_1/\varepsilon_0 A_0 v_g^2$ $=3.1\times10^4$ W^{-1}m^{-1}, $P=500$ mW, [$L_{NL}=(\gamma P)^{-1}=0.067$ mm], $\beta_3=-0.219$ ps^3/m. Three types of GVD are analyzed: (i) $\beta_2=0$ (ZGVD), $L'_D = T_0^3/|\beta_3| =$ 1.6 mm, $\tilde{N} = \sqrt{L'_D/L_{NL}}$ =4.9. (ii) $\beta_2=2.5\sim20$ ps^2/m (DCW), $L_D=T_0^2/|\beta_2|=0.26\sim2.0$ mm, $N=\sqrt{L_D/L_{NL}}$ =2.0~5.5. (iii) $\beta_2=-2.5$ ps^2/m (anomalous GVD), $L_D=2.0$ mm, $N=5.5$, soliton period $z_0=3.1$ mm. The adiabatic $\beta_2(z)$-curve in the DCW case is chosen such that about 90% of optical power lies in normal dispersion regime during propagation. We assume β_3 does not change with β_2 as treated in [7].

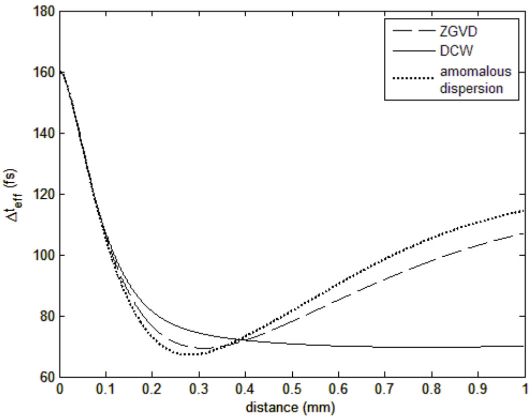

Fig.2. Effective pulse width Δt_{eff} versus propagation distance for ZGVD (dashed), DCW (solid), and anomalous GVD (dotted).

Fig. 2 shows the effective pulse width Δt_{eff} [defined as $\left(\int I(t)dt\right)^2 / \int I^2(t)dt$, where $I(t)$ is the intensity profile of transform-limited pulse] versus propagation distance z.
In the ZGVD case, Δt_{eff} reaches a minimum of 69 fs when the pulse only travels 0.31 mm. However, SPM does not continue to reduce Δt_{eff} (broaden the spectrum) even the peak intensity remains strong. This is attributed to the fact that the interplay between residual TOD and SPM causes temporal and spectral fine structures or sidelobes. As a result, optical power will be gradually moved toward the spectral wings, leaving a "hole" in the vicinity of spectral center [Fig. 3(a)]. The corresponding transform-limited pulse will have a narrow mainlobe, but with significant sidelobes or pedistal (Δt_{eff} is large). In the DCW case, Δt_{eff} is reduced at a slower rate and saturates (at ~70 fs) when the peak intensity becomes too weak to further broaden the spectrum by SPM. Further propagation of the pulse will simply incur up-chirp and require dispersion compensation to compress it to the transform-limit. The spectrum is free of sidelobes [Fig. 3(b)], allowing for high-quality transform-limited pulse. The flat $\Delta t_{eff}(z)$-curve implies that DCW has larger tolerance about variation of waveguide distance or input power, which are important in practical applications. Soliton pulse compression in the anomalous dispersion waveguide is as effectively as expected in [4] due to the existence of linear loss, TPA, and TOD. The optimal distance ($z_{opt}\approx$ 0.3 mm) is still consistent with that predicted by [4].

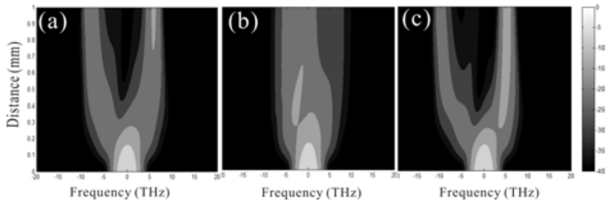

Fig.3. Power spectrum (dB scale) evolution as the Gaussian pulse propagates through waveguide with (a) ZGVD, (b) increasing normal dispersion, and (c) anomalous GVD.

4. Conclusions

We have numerically investigated the behavior of ultrashort pulse propagation in silicon nanowire waveguide with small and longitudinally incrasing normal dispersion. This scheme provides better spectral shape, higher stability, and compaitable spectral broadening compared with ZGVD and anomalous dispersion cases. This work is sponsered by National Science Council of Taiwan under grant: NSC 96-2112-M-007-016.

5. References

1) M.-C. M. Lee, W.-C. Chiu, T.-M. Yang, C.-H. Chen: Appl. Phys. Lett., **91** (2007), 191114.
2) H. Rong, A. Liu, R. Jones, O. Cohen, D. Hak, R. Nicholaescu, A. Fang, M. Paniccia: Nature **433** (2005), 292.
3) K.R. Tamura, H Kubota, M. Nagazawa: IEEE J. Quantum. Electron. **36** (2000), 773.
4) G.P. Agrawal: Nonlinear fiber optics, Academic Press, (1995).
5) R. Salem, M. A. Foster, A. C. Turner, D. F. Geraghty, M. Lipson, A. L. Gaeta: Opt. Express, **15** (2007), 7802.
6) X. Chen, N. C. Panoiu, I. Hsieh, J. I. Dadap, R. M. Osgood, Jr.: IEEE Photon. Technol. Lett., **18** (2006), 2617.
7) T. Okuno, M. Onishi, M. Nishimura: IEEE Photon. Technol. Lett., **10** (1998), 72.
8) A. C. Turner, C. Manolatou, B. S. Schmidt, M. Lipson, M. A. Foster, J. E. Sharping, A. L. Gaeta: Opt. Express, **14** (2006), 4357.
9) G. Genty, S. Coen, P.-A. Lacourt, B. Kibler, J. M. Dudley: in preceeding of Nonlinear photonics, (2007), NThC2.
10) L. Yin, G. P. Agrawal: Opt. Lett. **32** (2007), 2031.