CONTROL OF GROUP VELOCITY DISPERSION IN SINGLE MODE FIBER BASED ON STIMULATED BRILLOUIN SCATTERING

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My beloved *Papa* and *Mama*

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ABSTRACT

Slow light study is discussed in various methods of generation, materials and approaches. In this study, the control of group velocity, V_g and group velocity dispersion (GVD) of a pulse propagating in optical fiber is simulated and demonstrated. The slow light generation, which is closely related to V_g of a light pulse for this study is based on stimulated Brillouin scattering (SBS), the most efficient approach as reported by previous researchers. By using Matlab R2011b software, the slow light generation is simulated for the slow light structure in the form of hollow conical shape resonator, focusing on the geometrical parameters. The simulation work is extended to the control of V_g and GVD, to investigate the influences of refractive index of the materials and wave number of the light pulses. While most of slow light researches neglect the effect of dispersion, this study explicitly includes the second term of the wave number's expansion to represent GVD. Therefore, the experimental work investigates the creation of a strongly dispersive material with large chirp and small group delay via SBS in a highly-nonlinear optical fiber as opposed to previous SBS experiments which mainly focus on the creation of a slow light material with minimum dispersion and chirp. To demonstrate the control of V_g and GVD, a two-frequency pump field which consists of two distributed feedback lasers with the relative frequency separation nearly twice the Brillouin frequency and a slow light medium in the form of a 2-km high nonlinear single mode optical fiber are employed. For input field with slowly varying amplitude, the experiment obtained output pulses with large GVD and decreased intensity. All-optical control of the GVD is demonstrated by measuring the linear frequency chirp impressed on a 28-nanosecond-duration optical pulse and it is tunable over the range of ± 7.8 $ns^2\ m^{-1}$. In addition, the maximum observed value of GVD is 10^9 times larger than that obtained in a typical single-mode silica optical fiber. The simulation results for Gaussian pulses as input signal are in good agreement with the experimental ones, and therefore the control of V_g and GVD for different shapes of input pulses using the developed system can be predicted.

ABSTRAK

Kajian cahaya lambat dibincangkan dalam pelbagai kaedah penjanaan, bahan dan pendekatannya. Dalam kajian ini, kawalan halaju kumpulan (V_g) dan penyebaran halaju kumpulan (GVD) bagi denyut yang merambat melalui gentian optik disimulasi dan didemonstrasikan. Penghasilan cahaya lambat yang sangat berkait rapat dengan V_g denyut cahaya bagi kajian ini ialah berdasarkan Serakan Brillouin Terangsang (SBS), pendekatan paling berkesan yang pernah dilaporkan. Dengan menggunakan perisian Matlab R2011b, penjanaan cahaya lambat disimulasikan dengan struktur cahaya lambatnya ialah resonator berbentuk kon, khusus kepada parameter geometrinya. Kerja simulasi diperluaskan kepada kawalan V_g dan GVD, bagi mengkaji pengaruh indeks biasan bahan dan nombor gelombang denyut cahaya. Sementara kebanyakan kajian cahaya lambat mengabaikan kesan penyebaran, dalam kajian ini, terma kedua pengembangan nombor gelombang yang menentukan GVD diambilkira. Maka, kerja eksperimen dalam kajian ini menyiasat penghasilan bahan penyerakan yang kuat dengan kicauan besar dan kelewatan kumpulan yang kecil melalui SBS dalam gentian optik dengan ketidaklinearan tinggi, berbeza dengan eksperimen SBS sebelum ini yang kebanyakannya memfokus kepada penghasilan bahan cahaya lambat dengan penyebaran dan kicauan minimum. Bagi mengawal V_g dan GVD, satu medan dwi-frekuensi yang terdiri daripada dua laser pulangan teragih dengan beza frekuensi relatif hampir dua kali frekuensi Brillouin dan medium cahaya lambat iaitu 2 km gentian optik dengan ketidaklinearan tinggi digunakan. Kawalan penuh GVD dilaksanakan dengan mengukur kicauan frekuensi linear terkesan pada isyarat denyut optik bertempoh 28 nanosaat dan ianya boleh diubah dalam julat ± 7.8 $ns^2\ m^{-1}$. Selain itu, nilai maksimum GVD yang diperoleh adalah 10^9 kali lebih besar daripada yang didapati dengan menggunakan gentian optik mod tunggal biasa. Hasil simulasi bagi isyarat input berbentuk Gaussian bersesuaian dengan hasil pengamatan eksperimen, maka, kawalan V_g dan GVD bagi pelbagai bentuk isyarat lain dengan menggunakan sistem yang telah dibina boleh ditentukan.

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LIST OF ABBREVIATIONS

AC	-	Alternating current
BS	-	Beam splitter
CPA	-	Chirped-pulse amplification
CROW	-	Coupled resonator optical waveguide
CRS	-	Coupled resonator structure
DC	-	Direct current
DFB	-	Distributed feedback
EIT	-	Electromagnetically induced transparency
EDFA	-	Erbium-doped fiber amplifier
FPC	-	Fiber polarization controller
FWM	-	Four wave mixing
FWHM	-	Full width at half maximum
GVD	-	Group velocity dispersion
HNLF	-	Highly-nonlinear optical fiber
MZM	-	Mach-Zehnder modulator
OOK	-	On-off keying
OC	-	Optical circulator
PhC	-	Photonic crystal
PC	-	Polarization controller
RF	-	Radio frequency

SCISSOR	-	Side-coupled integrated spaced sequence of resonator
SMF	-	Single mode fiber
SF	-	Standard fiber
SBS	-	Stimulated Brillouin scattering
SIPS	-	Stimulated interpolarization scattering
SRS	-	Stimulated Raman scattering
SRLS	-	Stimulated Raman-like scattering
WGM	-	Whispering gallery mode

LIST OF SYMBOLS

θ	-	Angle
ω	-	Angular frequency
ω_s	-	Angular frequency
Ω_B	-	Brillouin frequency
ω_B	-	Brillouin frequency shift
g_B	-	Brillouin gain coeffecient
Γ_B	-	Brillouin linewidth
γ	-	Coupling coefficient of the resonator
l_e	-	Dimension of the evanescent field in the air outside the resonator
L_D	-	Dispersive length
A_{eff}	-	Effective area of the fiber
E	-	Electric field envelope
n_f	-	Fiber modal index of refraction
F	-	Finesse
Δ	-	Frequency separation between optical fields
γ	-	Full width at halfo maximum of stimulated Brillouin scattering resonance
G	-	Gain in decibel
T_g	-	Group delay
n_{fg}	-	Group index in the absence of any fiber nonlinearity
n_g	-	Group refractive index
V_g	-	Group velocity
β_2	-	Group velocity dispersion parameter
Im	-	Imaginary

I_{in}	-	Input intensity
T_i	-	Input pulse width
l	-	Length
L	-	Length of light propagation
α	-	Optical fiber losses
I_{out}	-	Output intensity
T_{out}	-	Output pulse width
g_0	-	Peak gain factor at the Brillouin gain spectrum
G_{Peak}	-	Peak of Brillouin gain
ε	-	Permittivity
B	-	Propagation constant
z	-	Propagation direction
B	-	Pulse broadening factor
τ_p	-	Pulse width
I_p	-	Pump light intensity
P_p		Pump power of the fiber
n	-	Refractive index
n_1	-	Refractive index of the fiber cladding layer
n_2	-	Refractive index of the fiber core
a	-	Rod radius
l_g	-	Separation gap between fibers
c	-	Speed of light in vacuum
E_s	-	Stokes field
I_s	-	Stokes intensity
X	-	Susceptibility
A_0	-	Thickness
t	-	Time
ε_0	-	Vacuum permittivity
k	-	Wave number
λ	-	wavelength of the light in vacuum

CHAPTER 1

INTRODUCTION

1.1 Overview

Light travels as fast as 3 x 10^8 ms^{-1} or precisely, 2.9792 458 x10^8 ms^{-1}. It is known globally as *c*, the speed of light when in travels through vacuum. When light travels through a material, the speed of the light is reduced so it becomes smaller than *c*. It is because the phase velocity is modified, caused by the physical phenomena for example refraction. This reduced velocity is defined as the changes of *c* to the phase velocity of light. Therefore, slow light is not caused by the phase velocity change but it happens because of the large reduction of the group velocity of light. Small frequency and wave numbers spreading of a group of waves lead to similarly an envelope with group velocity. The group of waves consists of carrier wave with phase velocity. Then, it can be fast light or slow light depends on that group velocity of light. When an optical pulse propagates at a very low group velocity, it is called as slow light. If it travels at a faster group velocity compared to speed of light in vacuum, it is called as fast light. Slow light happens when a pulse propagates and interacts with the medium it passes through, which reduces its group velocity [1]. Fast light and slow light are closely related to varied group refractive index of the medium where the light propagated. By knowing that the group refractive index of vacuum is 1; when the medium's group refractive index is less than 1, the medium is called as a fast light medium since the pulse light travelled through the medium faster compared to vacuum. Meanwhile, when the group refractive index of the medium is more than 1, the medium is a slow light medium, which leads to the light pulse delay phenomenon.

There are a number of techniques to generate slow light proposed and demonstrated by many research groups around the world. The techniques are basically categorized into two main groups which are material dispersion and waveguide dispersion. The example of material dispersion schemes are electromagnetically induced transparency (EIT) [2] and various type four wave mixing (FWM) [3, 4]. On the other hand, schemes of waveguide dispersion are such as by using photonic crystals [5], coupled resonator optical waveguide (CROW) [6] and various micro-resonator structures such as vertically-coupled resonator [7], which is included in this study.

Other than the method to generate slow light, the physics phenomena involved and discussed in slow light generation are also varied. Stimulated Brillouin scattering (SBS) is a nonlinear phenomenon and one of the approaches in slow light study, that turns out to be the most efficient approach for light propagation through silica, the main material for optical fibers; compared to other approaches such as Raman scattering and forward stimulated interpolarization scattering [1]. Therefore, the demonstration of Brillouin slow light in optical fiber become rapidly developed and leads to the importance of this study.

If the group velocity in a medium is varied by frequency, new physics is introduced, known as group velocity dispersion (GVD). In other word, GVD is the derivative of the inverse group velocity with respect to angular frequency. For typical fast and slow light study, this GVD is equal to zero and the light pulse is only modified in term of its propagating time. No dispersion issue is considered. However, when the dispersion of the light pulse is considered, which means GVD is controlled and made as large as possible, a light pulse will be broadened while the amplitude or intensity is decreased. The broadened and decreased amplitude of light pulse promises some applications in optics, such as avoiding damage to optical components, realization of chirped pulse amplification and the usage of time lens. However, for optical fibers, the GVD is usually defined as a derivative with respect to wavelength, rather than angular frequency.

In this study, the theory of slow light is explored, the generation and control of slow light are discussed, the dispersion of group velocity is studied and nonlinear phenomena used as approaches to explain the pulse propagation in optical fiber are simulated and experimentally demonstrated.

In optical fiber telecommunication, some of applications of slow light and GVD controls are optical memories and buffering, which are the important and needed technologies in future optical interconnections for computer systems and optical packet-switched networks to minimize traffic contention. Contention is the planning rules for shared links. A traffic contention happens when the demand for a shared link is larger compared to the link actually capability. The enhancement of slow light and GVD modification could improve future telecommunication sytem, which makes this study necessary and promises practical findings. Thus, this study focuses on both parts; controlling the slow light and GVD of an optical system.

1.2 Problem Statement

Researchers keep finding out the ideas of more possible techniques to demonstrate the slow light generation. It is including the slow light generation in different media, such as atomic vapours, semiconductors, and optical fiber. In this study, optical fiber is used as the slow light material since it offers a number of advantages for telecommunication application. The examples of application aimed are optical storage and optical buffering. On the other hand, the light's velocity when it travels through vacuum, c, is fast enough, which is 30 cm in a nanosecond, creating an advantage to efficiently transmit data or signal between two points, in very small or very big scale. However, it is difficult to modify the optical signals in the time domain. Since it is important to solve this problem, therefore, slow light technology is now being rapidly investigated [8]. While most of slow light researches focus on neglecting the dispersion, this study considers extending the slow light study to the group velocity dispersion (GVD) phenomenon to suit a number of applications in optical systems. The promising applications are such as quantum key distribution, quantum and classical information processing, and temporal cloaking require or can benefit from large GVD that can disperse longer-duration pulses. In these applications, optical pulse durations are typically in the sub-nanosecond regime for classical and quantum optical fiber telecommunication [9]. Previous research on GVD is limited to the domain of ultra-fast light pulses [10], and therefore, it heavily relies on complicated and specified devices for picoseconds laser pulse generation. Instead of focusing on the group velocity with zero or neglected dispersion, the control of GVD is studied as it makes controlling the pulse intensity better, which can minimize damage to optical devices. Furthermore, it is also important for a number of applications such as pulse chirp amplification and time lens [11]. Previous SBS experiments typically focused on the creation of a slow light material with minimal dispersion and chirp [9]. Therefore, it is another room of findings by investigating the creation of a strongly dispersive material with large chirp and small group delay via SBS in optical fiber.

1.3 Objectives of Study

1.3.1 General Objective

The general objective of this study is to simulate and demonstrate the control of group velocity, V_g and group velocity dispersion (GVD) of a pulse propagating in optical fiber via Stimulated Brillouin Scattering (SBS) using computer programming approach and experimental diagnostics.

1.3.2 Specific Objectives

The specific objectives of this study are :

- To design the optical fibers as slow light structure based on SBS. The slow light parameters are simulated together with the resonator in conical shape as the slow light structure.

- To simulate the light pulse propagating through the single mode optical fibers based on SBS by deriving from the group velocity, V_g to GVD. It is necessary to predict the effects of group velocity, V_g and GVD for various refractive indexes of the material and wave number of light pulse.

- To demonstrate the control of group velocity, V_g and GVD using SBS via optical fiber by doing experiment with a two-frequency pump as the light source.

1.4 Scope of Study

To simulate the group velocity, V_g and GVD of a pulse propagating in optical fiber via SBS, Matlab software version R2011b is used. The simulation work focuses on two parts. The first part is simulating the slow light parameters within a resonator in hollow conical shape as the slow light structure. There are many resonator structures suggested as slow light structure but for this study, vertically-coupled resonator structure is chosen. The parameters of the structure focussed are the geometrical parameters such as the radius of the resonator and the separation gap, neglecting the structural ones.

For the second part of the simulation work, the light pulse propagating through the single mode optical fibers based on SBS is simulated. It is done by deriving from the group velocity, V_g to GVD to investigate the affects of dispersion. The effects of group velocity, V_g and GVD for various group refractive indexes of the material and wave number of light pulse are predicted by simulating the equations related. From the value of V_g, the theoretical explanation is expanded to the GVD by considering few more parameters in wave number. The parameters considered are derived by Taylor expansion, and then the first three terms are considered.

Next, the experimental diagnostics completes this study. The group delay and control of GVD are demonstrated throughout the medium of a 2 km high nonlinear single mode optical fiber as the medium under test. The experiment demonstrates the slow light generation based on SBS via the fiber, which is a commercially-available photonic crystal fiber with highly-nonlinear properties to suit optical communication application. The relative frequency separation of the optical fields is nearly twice the Brillouin frequency which is set by controlling the light source, the two-frequency pump. Distributed feedback lasers are used as the two-frequency pump act as the signal beam and pump beam to generate SBS. A number of optical components are used in the experimental setup including Mach-Zehnder modulator (MZM), which is often realized in photonic integrated circuits for optical data transmission. For this study, a MZM with ~8dB loss from EOSpace was used. It is operated in carrier-suppressed mode, which is near zero power transmission and driven by a signal generator. The signal generator is from Agilent E8267D and operated from 250 kHz to 20 GHz, has output of 3.9 V sinusoidal signal at a frequency. A number of fiber polarization controllers with ~95% transmission were used to set the pump beam polarization such that the SBS interaction is maximized.

Finally, the detector with the specification New Focus 1611 with 1mW max linear, 1mV/µW DC output, 0.07 mV/µW AC output, and 1 GHz bandwidth reads the signal transmitted through the setup. The parameters of the output pulses are analyzed in various variables and considerations. The variables analyzed are such as the output pulse width and gain while the considerations taken into accounts are like the pulse sequences and frequency separation between gain (Stokes) and absorption line (anti Stokes), generated from SBS phenomenon.

1.5 Significance of Study

The purpose of this research is to simulate the slow light structure and system that can efficiently control the slow light to group velocity dispersion (GVD) for applications. The control of light pulse group velocity and GVD are important for the compatibility with a number of technologies, including in optical telecommunication and optical devices enhancement, benefited from SBS phenomenon. The computer programming simulation aims an optimized slow light structure based on SBS by using the vertically-coupled resonator. Defining the geometrical parameter that is most significant in controlling the group velocity of light passing through the resonator leads a number of options for slow light structure or medium.

Next, from the group velocity study, by predicting the wave number's influence on the light pulse considers GVD phenomenon. This is helpful in improving an optical device since it considers dispersion, which happens in real optical system. The GVD computer simulation and experiment diagnostics can describe the dependence of pulse gain, pulse width and frequency separation many more conditions to the pulse propagation through the slow light system. This will lead to the better control of the GVD system for application in telecommunication and protection of optical devices. For example, larger GVD results a broader pulse in time domain, which leads to reduced intensity. The lower intensity which represents the power of the pulse can minimize or avoid damage to the optical devices, without losing the information brought by the pulse. Furthermore, this research contributes to the technology of longer-duration pulses dispersion required or can be benefited to emerging application such as quantum key distribution, quantum and classical information processing, and temporal cloaking [9].

1.6 Thesis Outline

This thesis reports on the control of group velocity dispersion in optical fiber based on stimulated Brillouin scattering. It consists of seven chapters according to the study flow. Firstly, Chapter 1 introduces the study by firstly gives overview of the study, followed by the motivation of this study and states the general and specific objectives. The scopes of this study are presented together with the summary of the research methodology before completed with the importance of this study.

Chapter 2 presents the literature review of slow light study, then expanded to the group velocity dispersion research, included theoretical documentation and experimental demonstration. The review is focussed on the approach of stimulated Brillouin scattering phenomenon to generate slow light and to control the group velocity dispersion of the light pulse. The review also includes a number of techniques to generate slow light, various slow light structures and Brillouin slow light in optical. Chapter 3 summarizes the fundamental understanding for this study, which includes the theory of light propagation in slow light generation and group velocity dispersion control based on stimulated Brillouin scattering phenomenon. The physics of the phenomenon is discussed as it is an important theory for the computer programming work and the explanation of the experimental work.

Chapter 4 explains the steps of simulation work for the chosen slow light structure, expanded to the simulation of group delay and dispersion for the light pulse propagating through the optical fiber, based on stimulated Brillouin scattering approach. Chapter 5 completes the research methodology of this study by focusing on the experimental demonstration. The experiment demonstrate group delay and group dispersion velocity of the Gaussian light pulse generated from distributed feedback diode lasers through the highly-nonlinear single mode fiber. The experiment setup is presented in details in this chapter.

Chapter 6 has the observation and analysis of the result from both simulation and experimental works. This chapter shows the findings and explains the physics behind the results.

Finally, Chapter 7 completes this thesis with the summary of the findings and suggestions of future work for the continuity of this research field.

REFERENCES

[1] J. B. Khurgin and R. S. Tucker, *Slow Light Science and Applications*. Boca Raton: CRS Press, Taylor & Francis Group, 2009.

[2] J. B. Khurgin, "Optical buffers based on slow light in electromagnetically induced transparent media and coupled resonator structures : comparative analysis," *Optical Society of America*, vol. 22, no. 5, pp. 1062–1074, 2005.

[3] K. Nakajima, M. Ohashi, K. Shiraki, T. Horiguchi, and S. Member, "Four-Wave Mixing Suppression Effect of Dispersion Distributed Fibers," *Journal of Lightwave Technology*, vol. 17, no. 10, pp. 1814–1822, 1999.

[4] S. Song, C. T. Allen, S. Member, K. R. Demarest, and R. Hui, "Intensity-Dependent Phase-Matching Effects on Four-Wave Mixing in Optical Fibers," *Journal of Lightwave Technology*, vol. 17, no. 11, pp. 2285–2290, 1999.

[5] J. Brosi, "Slow-Light Photonic Crystal Devices for High-Speed Optical Signal Processing," Universitat Karlsruhe, 2008.

[6] A. Yariv, Y. Xu, R. K. Lee, and A. Scherer, "Coupled-Resonator Optical Waveguide : A Proposal and Analysis.," *Optics Letters*, vol. 24, no. 11, pp. 711–3, Jun. 1999.

[7] A. B. Matsko, A. A. Savchenkov, and L. Maleki, "Vertically Coupled Whispering-Gallery-Mode Resonator Waveguide," *Optics Letters*, vol. 30, no. 22, pp. 3066–3068, 2005.

[8] T. Baba, "Slow Light in Photonic Crystals," *Nature Photonics*, vol. 2, pp. 465–473, 2008.

[9] Y. Zhu, J. A. Greenberg, N. A. Husein, and D. J. Gauthier, "Giant all-optical tunable group velocity dispersion in an optical fiber," *Optics Express*, vol. 22, no. 12, pp. 9995–10002, 2014.

[10] A. M. Weiner, *Ultrafast Optics*. Hoboken, NJ, USA: John Wiley & Sons, Inc., 2009.

[11] L. E. Munioz-camuniez, V. Torres-company, J. Lancis, J. Ojeda-castañeda, and P. Andrés, “Electro-optic Time Lens with an Extended Time Aperture,” *Optical Society of America*, vol. 27, no. 10, pp. 2110–2115, 2010.

[12] R. Boyd, O. Hess, C. Denz, and E. Paspalakis, “Slow Light,” *Journal of Optics*, vol. 12, no. 10, pp. 100301–100301, Oct. 2010.

[13] A. Melloni and F. Morichetti, “The long march of slow photonics,” *Nature Photonics*, vol. 3, no. 3, pp. 119–119, Mar. 2009.

[14] M. S. Bigelow, N. N. Lepeshkin, and R. W. Boyd, “Superluminal and Slow Light Propagation in A Room-Temperature Solid,” *Science*, vol. 301, no. 5630, pp. 200–2, Jul. 2003.

[15] E. Wisniewski-Barker, G. Gibson, S. Franke-Arnold, Z. Shi, P. Narum, R. W. Boyd, and M. J. Padgett, “Slow light in ruby: delaying energy beyond the input pulse,” *Proceeding of the SPIE*, vol. 9378, p. 93780D, Mar. 2015.

[16] X. Shen, B. He, J. Zhao, Y. Liu, D. Bai, K. Yang, C. Wang, G. Liu, D. Luo, F. Liu, Q. Hao, W. Li, and H. Zeng, “Repetition rate stabilization of an erbium-doped all-fiber laser via opto-mechanical control of the intracavity group velocity,” *Applied Physics Letters*, vol. 106, no. 3, p. 031117, Jan. 2015.

[17] T. F. Krauss, “Why do we need slow light ?,” *Nature Photonics*, vol. 2, no. August, pp. 448–450, 2008.

[18] Z. Shi, R. Boyd, R. Camacho, P. Vudyasetu, and J. Howell, “Slow-Light Fourier Transform Interferometer,” *Physical Review Letters*, vol. 99, no. 24, p. 240801, Dec. 2007.

[19] Z. Shi, R. W. Boyd, D. J. Gauthier, and C. C. Dudley, “Enhancing the Spectral Sensitivity of Interometers Using Slow-Light Media,” *Optics Letters*, vol. 32, no. 8, pp. 915–917, 2007.

[20] Z. Shi and R. W. Boyd, “Slow-light interferometry: practical limitations to spectroscopic performance,” *Journal of the Optical Society of America B*, vol. 25, no. 12, pp. C136–C143, Oct. 2008.

[21] E. F. Burmeister, D. J. Blumenthal, and J. E. Bowers, “A Comparison of Optical Buffering Technologies,” *Optical Switching and Networking*, vol. 5, no. 1, pp. 10–18, Mar. 2008.

[22] C. J. Chang-hasnain, P. Ku, and S. Member, “Variable Optical Buffer Using Slow Light in Semiconductor Nanostructures,” *Proceedings of the IEEE*, vol. 91, no. 11, pp. 1884–1897, 2003.

[23] R. C. A. Jr, S. Member, J. U. Pelegrini, H. Waldman, and S. Member, “A Generic-Traffic Optical Buffer Modeling for Asynchronous Optical Switching Networks,” *IEEE Communications Letters*, vol. 9, no. 2, pp. 175–177, 2005.

[24] S. G. Johnson, M. Ibanescu, E. Ippen, and J. D. Joannopoulos, "Photonic-Crystal Slow-Light Enhancement of Nonlinear Phase Sensitivity," *Optical Society of America*, vol. 19, no. 9, pp. 2052–2059, 2002.

[25] J. Li, L. O'Faolain, S. a. Schulz, and T. F. Krauss, "Low Loss Propagation in Slow Light Photonic Crystal Waveguides at Group Indices up to 60," *Photonics and Nanostructures - Fundamentals and Applications*, vol. 10, no. 4, pp. 589–593, Oct. 2012.

[26] R. W. Boyd and D. J. Gauthier, "Slow and Fast Light," North Carolina, 2001.

[27] D. Eger, S. Smartsev, O. Firstenberg, and N. Davidson, "Slow light and narrow resonances in electromagnetic-induced deflection," *Proceeding of the SPIE*, vol. 9378, p. 93781B, Mar. 2015.

[28] L. Thevenaz, "Slow and fast light in optical fibres," *Nature Photonics*, vol. 2, no. August, pp. 474–481, 2008.

[29] M. Karlsson, "Four-wave mixing in fibers with randomly varying zero-dispersion wavelength," *Optical Society of America*, vol. 15, no. 8, pp. 2269–2275, 1998.

[30] M. Eiselt, "Limits on WDM Systems Due to Four-Wave Mixing : A Statistical Approach," *Journal of Lightwave Technology*, vol. 17, no. 11, pp. 2261–2267, 1999.

[31] S. Song, C. T. Allen, S. Member, K. R. Demarest, and R. Hui, "Intensity-Dependent Phase-Matching Effects on Four-Wave Mixing in Optical Fibers," *Journal of Lightwave Technology*, vol. 17, no. 11, pp. 2285–2290, 1999.

[32] A. Evert, A. James, T. Hawkins, P. Foy, R. Stolen, P. Dragic, L. Dong, R. Rice, and J. Ballato, "Longitudinally-Graded Optical Fibers," *Optics Express*, vol. 20, no. 16, pp. 1614–1620, 2012.

[33] B. Corcoran, C. Monat, M. Pelusi, C. Grillet, T. P. White, and L. O. Faolain, "Optical performance monitoring at 640Gb / s via slow-light in a silicon nanowire," *Optics Express*, 2010.

[34] L. V. Hau, S. E. Harris, Z. Dutton, and C. H. Behroozi, "Light Speed Reduction to 17 Metres Per Second in An Ultracold Atomic Gas," *Nature*, vol. 397, no. February, pp. 594–598, 1999.

[35] R. W. Boyd, "Progress in Slow Light and Quantum Imaging Interest in Slow Light," Rochester, 2005.

[36] A. Turukhin, V. Sudarshanam, M. Shahriar, J. Musser, B. Ham, and P. Hemmer, "Observation of Ultraslow and Stored Light Pulses in a Solid," *Physical Review Letters*, vol. 88, no. 2, p. 023602, Dec. 2001.

[37] A. Figotin and I. Vitebskiy, “Slow Light in Photonic Crystals,” *Waves in Random and Complex Media*, vol. 16, no. 3, pp. 293–382, Aug. 2006.

[38] A. C. Liapis, Z. Shi, and R. W. Boyd, “Optimizing Photonic Crystal Waveguides for On-Chip Spectroscopic Applications.,” *Optics Express*, vol. 21, no. 8, pp. 10160–5, Apr. 2013.

[39] R. W. Boyd, “Material slow light and structural slow light: similarities and differences for nonlinear optics [Invited],” *Journal of the Optical Society of America B*, vol. 28, no. 12, p. A38, Dec. 2011.

[40] M. Bahadon, A. Abdolkarim, J. Ali, and P. P. Yupapin, “Slow light generation using microring resonators for optical buffer application,” *Optical Engineering*, vol. 51, no. 4, pp. 1–8, 2012.

[41] J. E. Heebner and R. W. Boyd, “` Slow ’ and ` fast ’ light in resonator-coupled waveguides,” *Journal of Modern Optics*, vol. 49, no. 14, pp. 2629–2636, 2002.

[42] J. Zhang, G. Hernandez, and Y. Zhu, “Slow Light With Cavity Electromagnetically Induced Transparency,” *Optics Letters*, vol. 33, no. 1, pp. 46–48, 2008.

[43] G. P. A. Kelley, Paul L, Ivan P. Kaminow, *Nonlinear Fiber Optics*, Third Edit. Academic Press, 2001, pp. 63–94.

[44] A. Boskovic, S. V Chernikov, J. R. Taylor, and O. A. Levring, “Direct Continuous-Wave Measurement of n2 in Various Types of Telecommunication Fiber at 1.55 mm,” *Optics Letters*, vol. 21, no. 24, pp. 1966–1968, 1996.

[45] E. L. Buckland and R. W. Boyd, “Measurement of the Frequency Response of the Electrostrictive Nonlinearity in Optical Fibers,” *Optics Letters*, vol. 22, no. 10, pp. 676–678, 1997.

[46] K. Li, Z. Xiong, G. D. Peng, and P. L. Chu, “Direct Measurement of Nonlinear Refractive Index With an All-Fibre Sagnac Interferometer,” *Optics Communications*, vol. 136, pp. 223–226, 1997.

[47] A. Fellegara, A. Melloni, and M. Martinelli, “Measurement of the Frequency Response Induced by Electrostriction in Optical Fibers,” *Optics Letters*, vol. 22, no. 21, pp. 1615–1617, 1997.

[48] A. Melloni, F. Morichetti, and M. Martinelli, “Optical Slow Wave Structures,” *Optics & Photonics News*, no. November 2003, pp. 44–48, 2003.

[49] M. S. Kang, A. Brenn, and P. S. J. Russell, “All-Optical Control of Gigahertz Acoustic Resonances by Forward Stimulated Interpolarization Scattering in a

Photonic Crystal Fiber," *Physical Review Letters*, vol. 153901, no. October, pp. 2–5, 2010.

[50] C. Monat, B. Corcoran, C. Grillet, M. Ebnali-Heidari, D. J. Moss, B. J. Eggleton, T. P. White, L. O'Faolain, and T. F. Krauss, "Slow Light Enhanced Nonlinear Effects in Silicon Photonic Crystal Waveguides," *Optical Society of America*, vol. 17, pp. 2944–2953, 2009.

[51] A. Kobyakov, M. Sauer, and D. Chowdhury, "Stimulated Brillouin Scattering in Optical Fibers," *Optical Society of America*, vol. 2, pp. 1–59, Dec. 2009.

[52] M. Nikl and P. A. Robert, "Brillouin Gain Spectrum Characterization in Single-Mode Optical Fibers," *Journal of Lightwave*, vol. 15, no. 10, pp. 1842–1851, 1997.

[53] K. Y. Song, M. Herráez, and L. Thévenaz, "Observation of Pulse Delaying and Advancement in Optical Fibers Using Stimulated Brillouin Scattering," *Optical Society of America*, vol. 13, no. 1, pp. 82–88, Jan. 2005.

[54] O. Frazão, J. M. Marques, J. L. Santos, M. B. Marques, and J. M. Baptista, "Brillouin Fibre Laser Discrete Sensor For Simultaneous Strain and Temperature Measurement," *Applied Physics B*, vol. 86, no. 3, pp. 555–558, Dec. 2006.

[55] L. Thévenaz, "Brillouin Distributed Time-Domain Sensing in Optical Fibers : State of the Art and Perspectives," *Frontiers of Optoelectronics in China*, vol. 3, no. 1, pp. 13–21, Jan. 2010.

[56] D. Gauthier, "Progress on Stopped Light and Large-Delay Slow Light in Optical Fibers," *Optical Society of America*, p. SWC1, 2007.

[57] P. P. Yupapin and N. Pornsuwancharoen, "Proposed Nonlinear Microring Resonator Arrangement for Stopping and Storing Light," *IEEE Photonics Technology Letters*, vol. 21, no. 6, pp. 404–406, Mar. 2009.

[58] M. González Herráez, K. Y. Song, and L. Thévenaz, "Arbitrary-bandwidth Brillouin Slow Light in Optical Fibers," *Optical Society of America*, vol. 14, no. 4, pp. 1395–1400, Feb. 2006.

[59] Z. Zhu and D. J. Gauthier, "Nearly transparent SBS slow light in an optical fiber.," *Optics express*, vol. 14, no. 16, pp. 7238–45, Aug. 2006.

[60] B. Dastmalchi, P. Tassin, T. Koschny, and C. M. Soukoulis, "Strong group-velocity dispersion compensation with phase-engineered sheet metamaterials," *Physical Review B*, vol. 89, no. 11, p. 115123, Mar. 2014.

[61] T. Baselt, C. Taudt, and P. Hartmann, "Group-velocity dispersion analysis of large mode-area doped fibers implemented in a laser cavity during operation," *Proceeding of the SPIE*, vol. 9344, no. 1, p. 93442P, Mar. 2015.

[62] M. Notomi, K. Yamada, a. Shinya, J. Takahashi, C. Takahashi, and I. Yokohama, "Extremely Large Group-Velocity Dispersion of Line-Defect Waveguides in Photonic Crystal Slabs," *Physical Review Letters*, vol. 87, no. 25, p. 253902, Nov. 2001.

[63] C. Milián and D. V Skryabin, "Soliton families and resonant radiation in a micro-ring resonator near zero group-velocity dispersion.," *Optics express*, vol. 22, no. 3, pp. 3732–9, Feb. 2014.

[64] C. P. J. Barty, T. Guo, C. Le Blanc, F. Raksi, J. Squier, K. R. Wilson, V. V Yakovlev, and K. Yamakawa, "Generation of 18-fs , Multiterawatt Pulses by Regenerative Pulse Shaping and Chirped-pulse Amplification," *Optics Letters*, vol. 21, no. 9, pp. 668–670, 1996.

[65] G. Mourou, "Generation of Ultrahigh Peak Power Pulses by Chirped Pulse Amplification," *IEEE Journal of Quantum Electronics*, vol. 24, no. 2, pp. 398–403, 1988.

[66] P. W. Milonni, *Series in Optics and Optoelectronics Fast Light , Slow Light and Left-Handed Light P W Milonni*. Los Alamos, New Mexico: IOP Publisihing Ltd., 2005.

[67] D. J. Gauthier and R. W. Boyd, "Fast Light , Slow Light and Optical Precursors : What Does It All Mean ? How can the group velocity of a pulse of light propagating through a dispersive material exceed the speed of light in vacuum without violating Einstein ' s special theory of relativi," *Photonic Spectra*, pp. 11–19.

[68] Lord Rayleigh, "On the Velocity of Light," *Nature*, vol. 24, p. 382, 1881.

[69] M. D. Crisp, "Concept of Velocity in Resonant Pulse Propagation," *Physical Review A*, vol. 4, no. 5, pp. 2104–2108, 1971.

[70] J. Hayes, *FOA Reference Guide To Fiber Optics*. Fallbrook: The Fiber Optic Association, Inc., 2009, pp. 1–6.

[71] P. W. Milonni, "Series in Optics and Optoelectronics Fast Light , Slow Light and Left-Handed Light P W Milonni," 2005.

[72] Y. Su, F. Liu, Q. Li, Z. Zhang, and M. Qiu, "System performance of slow-light buffering and storage in silicon," *Optical Transmission, Switching and Subsystem*, vol. 6783, pp. 1–8, 2007.

[73] S. Mookherjea, S. Member, A. Yariv, and L. Fellow, "Coupled Resonator Optical Waveguides," *Quantum Electronics*, vol. 8, no. 3, pp. 448–456, 2002.

[74] N. Stefanou and A. Modinos, "Impurity Bands in Photonic Insulators," *Physical Review B*, vol. 12127, no. May, pp. 1997–1999, 1998.

[75] J. E. Heebner and R. W. Boyd, "Slow and Stopped Light : 'Slow' and 'Fast' Light in Resonator-Coupled Waveguides," *Journal of Modern Optics*, vol. 49, no. 14–15, pp. 2629–2636, Nov. 2002.

[76] J. E. Heebner, R. W. Boyd, and Q. Park, "SCISSOR Solitons and Other Novel Propagation in Microresonator-modified Waveguides," *Optical Society of America*, vol. 19, no. 4, pp. 722–731, 2002.

[77] S. Mookherjea and A. Oh, "What is the velocity of slow light in weakly disordered optical slow-wave structures ? Ideal : Actual : Gaussian rv Uniform rv Band-tail," *Optical Society of America*, vol. 4, pp. 4–5, 2007.

[78] J. E. Heebner, "Nonlinear optical whispering gallery microresonators for photonics," The University of Rochester, United States, 2003.

[79] J. K. S. Poon, J. Scheuer, Y. Xu, and A. Yariv, "Designing coupled-resonator optical waveguide delay lines," *Journal of the Optical Society of America B*, vol. 21, no. 9, p. 1665, 2004.

[80] K. J. Vahala, "Optical Microcavities," *Nature*, vol. 424, no. August, pp. 839–846, 2003.

[81] H. J. S. Dorren, M. T. Hill, A. Member, Y. Liu, S. Member, N. Calabretta, A. Srivatsa, F. M. Huijskens, H. De Waardt, and G. D. Khoe, "Optical Packet Switching and Buffering by Using All-Optical Signal Processing Methods," *Journal of Lightwave*, vol. 21, no. 1, pp. 2–12, 2003.

[82] D. Dahan and G. Eisenstein, "Tunable All Optical Delay via Slow and Fast Light Propagation in a Raman Assisted Fiber Optical Parametric Amplifier : A Route to all Optical Buffering," *Optical Society of America*, vol. 13, no. 16, pp. 530–532, 2005.

[83] E. F. Burmeister, D. J. Blumenthal, and J. E. Bowers, "A comparison of optical buffering technologies," *Optical Switching and Networking*, vol. 5, no. 1, pp. 10–18, Mar. 2008.

[84] G. Lenz, B. J. Eggleton, C. K. Madsen, and R. E. Slusher, "Optical Delay Lines Based on Optical Filters," *IEEE Journal*, vol. 37, no. 4, pp. 525–532, 2001.

[85] R. W. Boyd, *Nonlinear Optics*. Academic Press, Amsterdam, 2008, p. Chapter 9.