1

Introduction

1.1 Thesis Approach:

In this thesis, we are mainly focused on slow light generation in an optical fibre based on the non-linear scattering of light. So, here we are designing and numerically modelling an extremely nonlinear step index bismuth oxide optical fibre operating on single mode conditions. There are many ways for generation of slow light but we have considered stimulated Brillouin scattering (SBS) for our analysis due to its numerous advantages over other techniques as discussed in the following chapters. We have opted wavelength range of the third optical window specifically 1550 nm for all estimations and analysis.

Software ‘Comsol Multiphysics’ has been used for performing modal analysis for the proposed fibre structure. This commercially accessible software’s working is based on finite element method. The effective mode area and confinement loss for the fundamental mode have been calculated using Comsol Multiphysics software. The proposed optical fibre design is studied for tuneable slow light and other parameters are obtained by developing MATLAB codes.

1.2 Thesis Objectives:

The key objectives of the thesis are as follows:

1. To study the classification, basic properties of the optical fibre and designing of different optical fibre models.
2. To study the fundamentals of slow light, various methods to achieve slow light especially stimulated Brillouin scattering and its applications in the future of optical communication.
3. To study the basics of various numerical methods which are used to model optical fibres like Finite Element Method, Finite Difference Method, Variational Method, Method of Moments.
4. Design and analysis of the step index bismuth oxide optical fibre for the generation of slow light for single mode operation.

5. To analyze the proposed optical fibre for achieving tunability of slow light.

1.3 Thesis Organisation:

The outcome of the work carried out in this project is organised into five chapters. Chapter 1 consists of the approach and objective of the thesis. Chapter 2 includes the understanding of the term ‘slow light’, literature review of the topic of the project, basics of slow light, stimulated Brillouin scattering and other non-linear phenomenon in optics. Chapter 3 includes the study of optical fibres, its types and structures. Chapter 4 explains the various numerical techniques for fibre analysis. Chapter 5 deals with the design of single-mode step index bismuth oxide optical fibre and its analysis for slow light applications. The project work is concluded in Chapter 6 along with the suggestions to the future work that can be done in this field.

2

Understanding Slow light

2.1 Introduction

“Slow light” is the term given to the phenomenon where the group velocity of a pulse travelling in a medium is greatly reduced than its phase velocity. Because the effect produced is that a light pulse exits an optical medium at a time later than would be predicted by simple consideration of the medium’s length and phase index.

There are various reasons to study slow light. Clearly, the concept of slow light is in direct opposition to our daily life experience of light travelling extremely fast. The fundamental interest is to have a deeper and better understanding of light propagation and light-matter interactions under circumstances where the effective velocity of light is much lower than the usually considered speed, c = 3×10^8 km/s. In addition, there is huge technological interest for improvement of optical devices where requirements such as power, low loss and compactness can be addressed with slow light concepts. One of the main issues in the modern communication links is electro–optical conversion where a lot of energy is lost and at the same time, the speed of information transfer is decreased. An all-optical integrated circuit that can substitute the role of electronics would significantly improve a communication link. For practical implementation, slow light could actually allow faster optical communication [1-3]. Additionally, there are many possible applications that have been proposed for slow light effects. Several possibilities within the field of communications include proposals for optical pulse re-centering, synchronization of time-division-multiplexers, and optical correlation [4]. Also, it has been demonstrated that slow light can be used to enhance the sensitivity of spectral interferometers [5,6].

A lot of research has been done to study velocity of light [7-10]. The concept of group velocity describes the propagating speed of the light pulse. Slow light refers to situations where group velocity is much smaller than the light velocity in the vacuum. In simple terms, we can obtain slow light in two ways. First, by changing dispersive properties of homogeneous media i.e., material dispersion with various schemes as electromagnetically induced transparency (EIT)

[11], coherent population oscillation(CPO) [12], stimulated Raman scattering (SBS) [13], stimulated Brillouin scattering (SBS) [14-16]. Second, by periodically pattering homogeneous dielectric media i.e waveguide/structural dispersion. In the first case, strong dispersion occurs due to atomic resonances while in the second case it is due to geometrical resonances. The famous experiment performed by Hau et al. [17] in 1999, belongs to the former example. Together with the co–workers she showed that light pulses can be slowed down to a speed of 17 m/s at ultracold atomic gas in a Bose-Einstein condensation. This experiment was definitely one of the milestones for the research in the slow light. Kash et al. [18] slowed light down to 90 m/s in rubidium vapour. This experiment was then refined by Budker et al. [19], and light was slowed down to 8 m/s. Finally, Bigelow et al. [20] could slow light down to less than 58 m/s at room temperature in a ruby crystal. Researchers have also used erbium-doped optical fibre for the slow light generation ([21,22]). Also, a different version of slow light was achieved by Liu et al. [23] and Walsworth et al. [24], who reported of stopping light entirely. In those experiments, data carried by light pulses was momentarily stored in the dispersive medium, permitting subsequent recreation of light pulses carrying the same data, with small losses. Previously, for the slow-light generation, silica fibres were used [25]. But to attain high time delay and Brillouin gain values the length of the fibre requires was in kilometre range [21]. So, for more practically suitable applications, high refractive index materials [26-29] and photonic crystal fibres [30] are being researched upon. Still, there is a need to explore features like tunable slow light, low power consumption and as these experiments require very complicated and large set–up that is impractical for any real application outside a lab environment. It is necessary to understand physics behind these processes in order to make more robust and reliable devices. Before going into phenomenon behind the slow light, lets first understand the velocity of light which we are trying to alter.

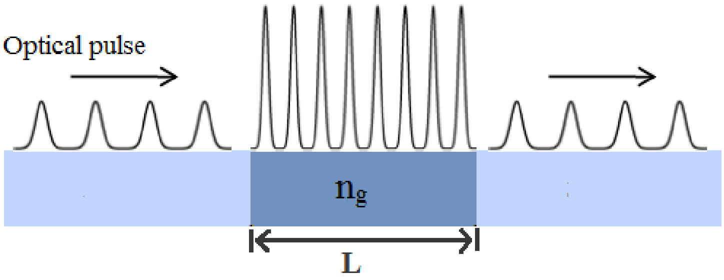


Figure 1: Slow Light in an optical fibre.

2.2 Types of velocities defined

We are going to discuss about different types of velocity defined. As before understanding the slow light phenomenon we need to understand velocities of light. Here, we are discussing the two most important velocities with respect to analysis (slow light generation) i.e. phase velocity and group velocity. There are also other types of velocities of light [31-33]. While generally referring to speed of light we are infact referring to light's phase velocity in the vacuum ($c=3x10^8$).

2.2.1 Phase Velocity

The velocity at which all points of the wave have a constant phase travel (e.g. the maxima or minima of a wave) is defined as phase velocity of a plane wave. When a wave travels inside a medium, its velocity is reduced by c/n where n is the refractive index of the medium and c speed of light in the vacuum but this reduction in velocity is a reduction in phase velocity. Whereas for slow light we require a reduction in group velocity.

Assume a monochromatic wave having an electric field, as a function of time t and distance z, defined as,

$$E(z,t) = \frac{1}{2}\left(E_0 e^{j(k(\omega)z-\omega t)} + c.c\right) \tag{2.1}$$

For the above equation, E_0 is the amplitude value, ω is wave's angular frequency, $k(\omega)$ is the frequency dependent wave number value and c.c. denotes complex conjugate part. If phase is denoted by φ and defined as in equation 2.2 from equation 2.1. As the phase value remains constant for a small-time interval dt, the differential of the equation 2.2 must be zero.

$$\varphi(z,t) = k(\omega)z - \omega t \tag{2.2}$$

$$\frac{d\varphi}{dt} = k(\omega)\frac{dz}{dt} - \omega = 0 \tag{2.3}$$

From equation 2.3, phase velocity can be defined as:

$$v_{ph} = \frac{dz}{dt} = \frac{\omega}{k(\omega)} = \frac{c}{n(\omega)} \tag{2.4}$$

The dependence of phase velocity on the refractive index of the medium in which the wave is travelling can be easily deduced from equation 2.4.

2.2.2 Group Velocity

The velocity of the overall shape of the wave amplitudes or envelope of the wave is called as group velocity as shown in figure 2. Parallel to the derivation of the phase velocity, the group velocity vg is given by:

$$v_g = \frac{dz}{dt} = \frac{d\omega}{dk} \tag{2.5}$$

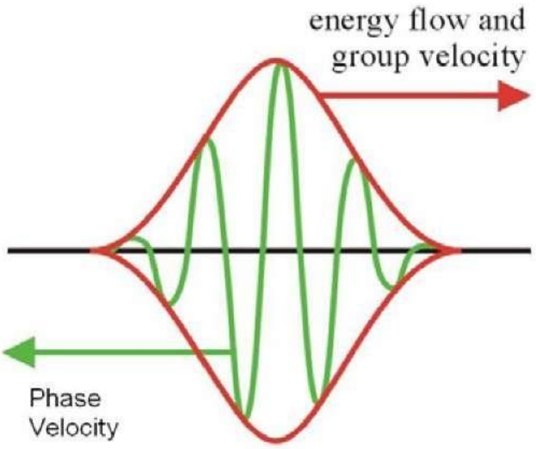


Figure 2: Pulse envelope propagating with vg and carrier frequency propagating with vφ.

2.3 Concept of nonlinearity in optical fibre

Slow light can be achieved using nonlinear effects of optical fibre. Nonlinearity or linearity corresponds to the response of the medium to light. When low intensity of light is used then there is nonlinearity observed. Nonlinearity is only observed when a very high intensity of light (Electromagnetic fields) is used. On a molecular level, nonlinear response of a medium is linked to anharmonic motion of bound electrons due to application of highly intense fields. This causes the polarization to follow the relation below with electric field as opposed to the linear relation of polarization directly proportional to the electric field.

$$P = \epsilon_0(\chi^{(1)}.E + \chi^{(2)}.EE + \chi^{(3)}.EEE + \cdots) \tag{2.6}$$

Here ϵ_0 is the vacuum permittivity and $\chi^{(j)}$ is jth order susceptibility. The nonlinearity in optical fibre is owed to third order susceptibility i.e. $\chi^{(3)}$.

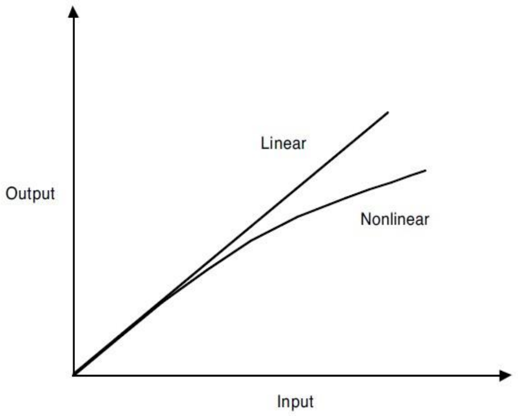


Figure 3: Graph depicting Linear and nonlinear interactions.

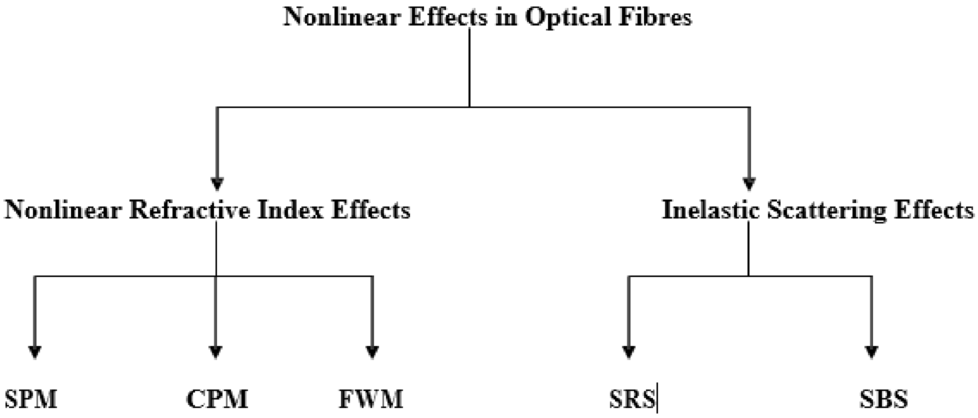


Figure 4: Nonlinear effects of optical fibres.

The occurrence of these nonlinear effects is due to intensity dependency of refractive index or scattering phenomenon [34]. So, the terms linear and nonlinear mainly means to the intensity independency or intensity dependency respectively. Due to the dependency of refractive index, there are three major effects namely Self Phase Modulation (SPM), Cross Phase Modulation (CPM) and Four Wave Mixing (FWM). Due to inelastic scattering, there are two major effects Stimulated Brillouin Scattering (SBS) and Stimulated Raman Scattering (SRS).

2.4 Methods of achieving slow light

2.4.1 Electromagnetically induced transparency (EIT)

Coherent quantum interference is the effect associated with the EIT method which can help in solving the problem of short duration storage of light. This method involves the creation of a transparent window in the absorption spectra so that the pulse can pass through it without any absorption taking place. This phenomenon is associated with the group velocity variation of the propagating pulse. Frequent variation of the normal dispersion and refractive index value are the two outcomes caused by the creation of the transparency window.

Electromagnetically induced transparency is a phenomenon in the field of science that turns originally present highly opaque medium into a transparent medium. When the atoms present in an opaque medium interact with an incident electromagnetic radiation, coherences are excited. These coherences being excited in the atoms of the medium interfere to produce what is called as electromagnetically induced transparency. This even leads to modification of the refractive properties associated with the medium [35, 36]. For example, high refractive index value of a medium is correlated to high absorption by that medium but as an effect of EIT, this correlation can be broken leading to the formation of media having various optical properties which are unusual in their existence. Harris et al. [37] were the first to discover the EIT method. He used a gas consisting of atoms which had three different energy levels associated with it and the quantum interference involved between the field probes was destructive in nature. Out of the two probes involved, tuning of one of the weaker probe was done near a transition wavelength of 283 nm and the other probe was tuned to a transition wavelength of 405.9 nm. This was done in a manner so that quantum interference of destructive type is formed between the involved probes.

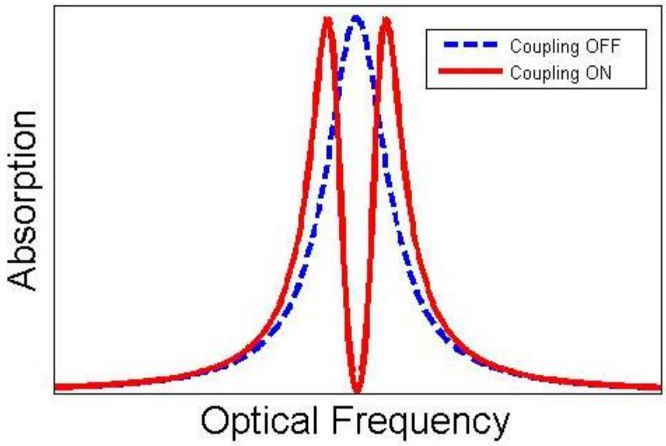


Figure 5: Electromagnetically induced transparency.

2.4.2 Coherent population oscillation (CPO)

The EIT method has an advanced and improved version which is called coherent population control method or CPO method. It is suitable for solids which are at room temperatures. Here, the group index of the medium in which the incident pulse is propagating is varied by the formation of a narrow spectral window in the absorption profile. In contrast to EIT method which involves quantum mechanical interference effect, the interference effects involved in CPO method is of two laser beams. The creation of this method requires two waves namely: weak wave and pump wave. Both the involved waves differ slightly in the frequency. The population of atoms present between the excited state and the ground state start oscillating when these two waves interact with each other. There are however two more essential conditions required for the interaction to create these oscillations and they are:

1. The pump wave must be strong enough.
2. Both the fields involved must be nearly resonant.

This method results in decrease of the absorption effect and efficient scattering of light from pump to the probe.

This method has various advantages which are as given below:

- a. In materials such as ruby [38] and erbium doped optical fibres [39], negative group velocities, fast-light and slow light can be achieved.
- b. It is suitable for various varieties of materials which are present at room temperatures and optical regime wavelengths
- c. With the help of this method, slow-light can be achieved in semiconductor materials.

The inverse of the population recovery time sets a narrow bandwidth associated to this method which is a disadvantage. Due to this, the bandwidth is limited to few KHz in some crystals and is the reason because of which pulses of more than 1 ms are allowed [40]

2.4.3 Stimulated Raman scattering (SRS)

Stimulated Brillouin Scattering (SRS) is a very useful nonlinear effect that can be used for broadband Raman amplifiers and Raman lasers. This phenomenon finds its base in spontaneous Raman scattering also known as Raman effect [41]. It was discovered in 1928 by Raman for which he received the Nobel Prize in Physics in 1930. In spontaneous Raman scattering, a small amount of power is transferred from one optical field to another i.e. we can transfer power from pump/source wave to the signal wave. In spontaneous Raman scattering, there can be three types of waves generated Stokes wave, anti-Stokes wave and Rayleigh as shown in figure 6. In 1962, it was experimentally seen that for highly intense electromagnetic fields Stokes wave generated rapidly and most of the pump/source wave power was transmitted to Stokes wave [42].

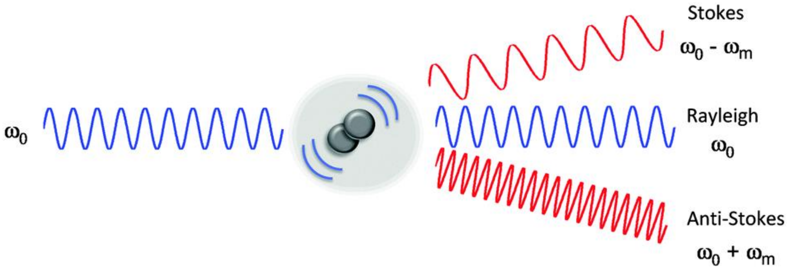


Figure 6: Spontaneous Raman Scattering.

2.4.4 Stimulated Brillouin scattering (SBS)

For the generation of slow light, we are using nonlinear effects of optical fibre namely Stimulated Brillouin scattering (SBS). This phenomenon was studied by a French physicist, Leon Brillouin. In Stimulated Brillouin scattering, the interaction of two counter propagating waves is considered, one is a very intense pump/source wave and other is a counter-propagating signal wave which is detuned in frequency [43,44]. This interaction produces an intensity wave of the frequency equal to the difference between the frequencies of the pump and signal wave. Now, due to electrostriction, the intensity wave so produced triggers travelling density variations, called acoustic wave, which in turn induces a travelling grating of refractive index variation in the optical fibre due to photo elastic effect. The process of SBS is diagrammatically explain in figure 7. The travelling grating so produced can strongly combine the optical power between the pump and signal waves at Brillouin frequency shift ($\Omega_{\boldsymbol{B}}$), which is a fibre dependent constant and provide gain.

If, ω_P is frequency of pump and ω_s is frequency of counter propagating signal wave with intensities I_p and I_s respectively. The signal and pump frequencies are related by $\omega_p - \omega_s = \Omega_{\boldsymbol{B}}$. Then, we can define coupled nonlinear differential equations for pump/source and signal waves by the following equations [25,45,46]

$$\frac{dI_p}{dz} = -g_B I_p I_s - \alpha_p I_p \tag{2.7}$$

$$-\frac{dI_s}{dz} = g_B I_p I_s - \alpha_s I_s \tag{2.8}$$

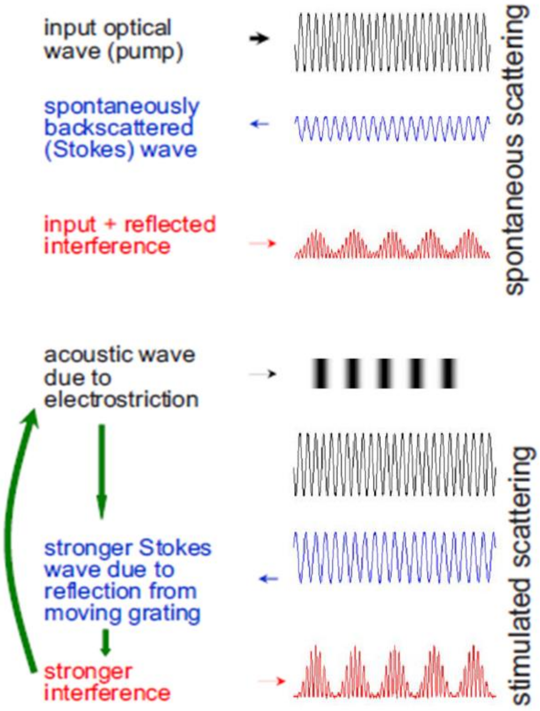


Figure 7: Process of Stimulated Brillouin Scattering.

By considering the pump wave as undepleted, and ($\alpha_p \approx \alpha_s$) = α, the result of the equations (2.7) & (2.8) is

$$I_s(0) = I_s(L) exp\left[\frac{g_B P_p L_{eff}}{A_{eff}} - \alpha L\right] \tag{2.9}$$

Here, real length of the optical fibre is denoted by L and the effective length of the optical fibre is denoted by L_{eff} (using equation 2.10), the attenuation constant for the fibre is denoted by α (a material dependent value), effective mode area for the propagating mode is denoted by A_{eff} (a design dependent value) (using equation 2.11), Brillouin gain coefficient is denoted by g_B (a material and frequency shift dependent value) and P_p is pump power,

with,

$$L_{eff} = \alpha^{-1}(1 - \exp(-\alpha L)) \tag{2.10}$$

$$A_{eff} = \frac{\left(\iint_{-\infty}^{\infty} |E|^2 \, dx \, dy\right)^2}{\left(\iint_{-\infty}^{\infty} |E|^4 \, dx \, dy\right)} \tag{2.11}$$

Here *E* is denoted by electric field distribution inside the core area of the fibre.

The Brillouin gain coefficient can be expressed as,

$$g_B(\Omega) = \frac{g_B(\Gamma_B/2)^2}{(\Omega - \Omega_B)^2 + (\Gamma_B/2)^2} \tag{2.12}$$

Here gp is the peak value of the Brillouin gain coefficient at $\Omega = \Omega_B$ and given by the relation

$$g_p = g_B(\Omega_B) = \frac{2\pi^2 n^7 p_{12}^2}{c\lambda_p^2 \rho_0 \upsilon_A \Gamma_B} \tag{2.13}$$

Here n is the refractive index, p_{12} is the longitudinal elasto-optic coefficient, c is the speed of light in vacuum, λ_p is pump wavelength, ρ_0 is the density, Γ_B is the Brillouin linewidth related to $\Delta\upsilon_B$ by the relation $\upsilon_B = \Gamma_B /(2\pi)$; where $\Delta\upsilon_B$ is Brillouin gain bandwidth. υ_A is acoustic velocity.

The Brillouin gain for the step index fibre can be estimated using the relation,

$$G = 10 \log \left(exp \left(\frac{g_B K P_p L_{eff}}{A_{eff}} - \alpha L \right) \right) \tag{2.14}$$

where P_p is the input pump power and K is the polarization factor which relies on the polarization properties of the optical fibre. If polarization is maintained then K's value is 1 and if polarization is not maintained then 0.5, however, some results [26,27,47] showed that K = 0.667 is more suitable, for the fibre which is low-birefringence and very high polarization beat length. Hence, in our simulation, K = 0.667 has been used.

The maximum permissible pump power, P_{max}, i.e., the maximum power level beyond which the output pulse get distorted, can be computed by subsequent relation,

$$P_{max} = 21 \frac{A_{eff}}{K g_B L_{eff}} \tag{2.15}$$

If input power advanced upto P_{max} then a backscattered wave will be generated from the background noise in the fibre, which induces grave pulse distortion/alteration. Hence, input power value must be lower than P_{max}. The least amount of pump power which is required to commence SBS effect, i.e., when overall gain in the fibre is positive or when total loss in fibre is lower than Brillouin gain value, is given by

$$P_{min} = \frac{\alpha A_{eff} L}{K g_B L_{eff}} \tag{2.16}$$

The SBS-induced time delay per unit length and per unit input pump power can be expressed as,

$$\frac{\Delta t_d}{P_P L_{eff}} = \frac{g_0 K}{\Gamma_B} \tag{2.17}$$

Where g_0 is line centre SBS gain coefficient, given by $g_0 = g_B/A_{eff}$.

Other significant parameters include time delay slop efficiency and FOM. For ensuring the aptness of optical fibres as a SBS based slow light medium, it is vital to estimate their FOM. S_{dg} and FOM of the fibre is defined as

$$S_{dg} = \frac{\Delta t_d}{G_B} = \frac{1}{8.686 \pi \Delta v_B} \tag{2.18}$$

$$FOM = \frac{G}{P_p\, L_{eff}\, n} \tag{2.19}$$

2.5 Few Benefits and Shortcomings of SBS based Slow light

Benefits

1. Firstly and most importantly, the power requirement for SBS to occur in an optical fibre is of the order of milliwatts (As shown by our results in chapter 5) i.e. Few milliwatts of pump power is enough for generation of substantial time delay. As time delay is directly dependent on pump/source power, the time delay can be easily tuned just by adjusting the pump power.
2. For any application to find practical usability is the working conditions required. Like for SBS phenomenon to occur we don't need special environment i.e. it can work at room temperature and for all range of wavelengths.

3. Also, there is no requirement of special fibres, the designed fibres can be used as a slow-light medium. Off-the-shelf telecommunication components can be used.

Shortcomings

1. The main shortcoming of SBS based slow light is that the saturation of time delay at higher pump powers i.e. there is an upper limit to which we can increase time delay or Brillouin gain value.
2. Also, due to the expansion of the pulse width with time delay in the optical fibre, this causes a drop in effective time delay.

2.6 Applications of slow-light

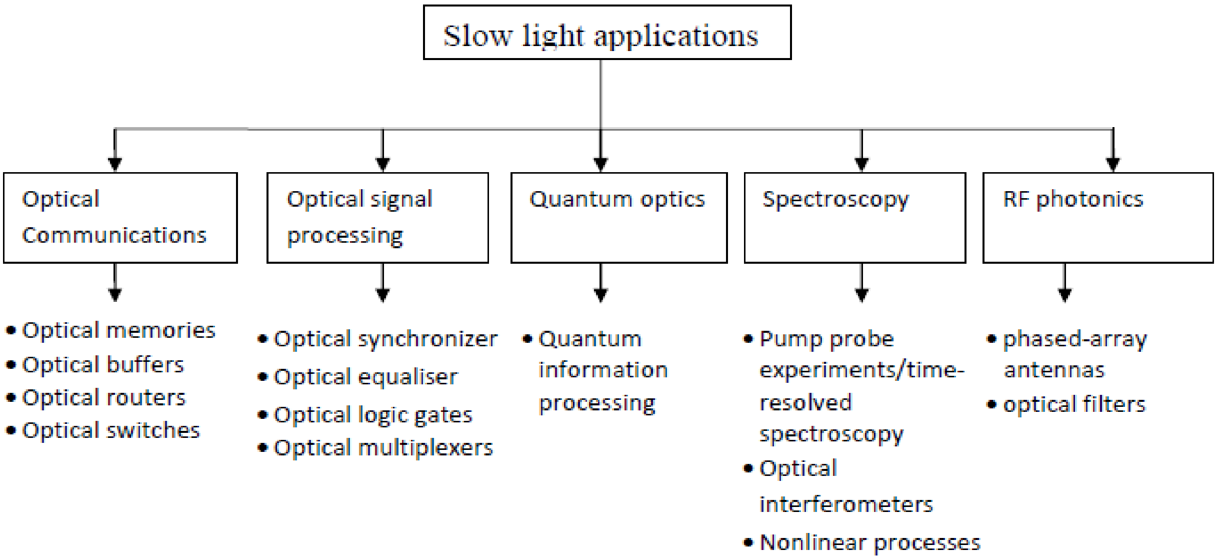
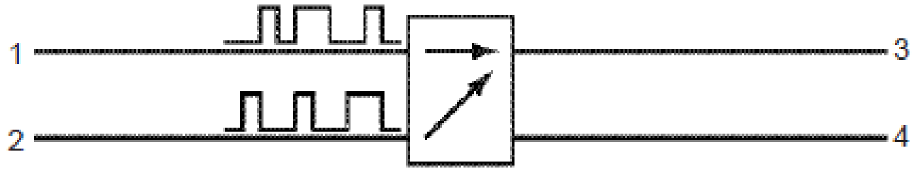


Figure 8: Flowchart of slow light applications.

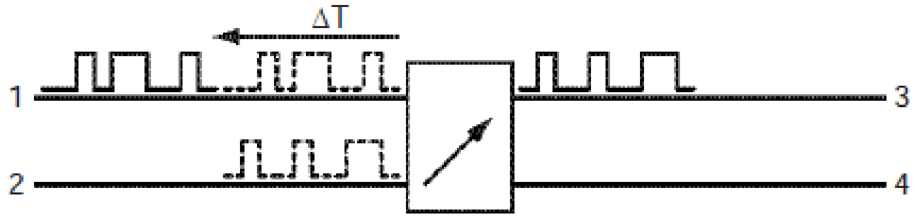
Slow light has found numerous practical application and also provided scientists with a technique to perform various other studies on the propagation of light. The practical applications of slow light are interdisciplinary like optical signal processing, all optical communication, quantum optics, RF photonics, etc. Slow light applications are shown in figure 8 and a few are described below.

2.6.1 Optical Buffers and Memories in Packed Switched Networks

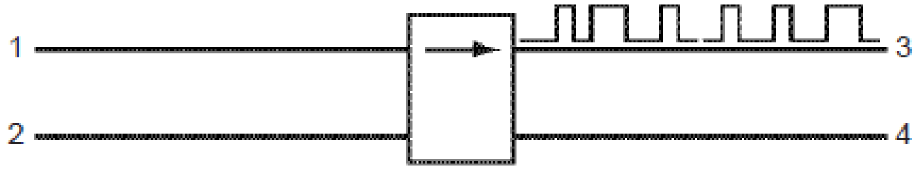
The ability to realize optical buffers and memories for packed switched networks is one of the foremost real-world application of slow light. Buffering of optical signals is one of the biggest roadblocks in the realization of All-optical communication systems. As presently we have optical fibre channels but at the transmitter receiver end, we are mainly using microwave-based systems so there a big mismatch with respect to the speed of data transmission. So, optical buffering through slow light can be used to resolve this problem. Also, drawback of using conventional buffers are that it has fixed fibre length, so only a fixed time delay is possible. Thus, these time delay buffers are not so effective for optical buffering application. But a slow light-based buffer system satisfies all the requirements. The slow light effect also finds its application for optical synchronization and multiplexing of multiple data channels in different optical fibres.



(a) Packet contention in a switch.



(b) Buffering of first packet and routing of second packet.



(c) Release and routing of first packet after second packed is routed.

Figure 9: Process of data transmission using a buffer.

The realization of optical packet switches and routers is one of the foremost applications of slow-light effect. Packet switching is essentially a mode of communication. In packet switching the information/data is divided into blocks and these blocks are known as packets. Internet is the most common and extensively used example of packet-switched network, in which packets are switched by various transmission paths by the router. But when two packets reach the router at the same time then there is a problem as this causes collision of packets.

Thus, storing of packets become necessary to allow the processing of each packet one by one [48]. Figure 9 shows the whole process of data transmission by using a buffer.

2.6.2 Slow light-based spectroscopy and interferometry

In slow light, we have observed that refractive index of material in optical fibre is a function of frequency. Because of this, a minute deviation in frequency value can drastically change wave number value. This dependency can be used in the field of spectroscopy. In time-resolved spectroscopy, characterization of the material is done by a pump probe configuration. In this process, two pulses with a time delay are sent to the sample for testing. The first pulse is aim is to vary the property of the sample and the second pulse is sent to interrogates those variations. Mechanical mechanisms are used to provide delay by changing the length of the path. This becomes a very complicated system. This total work of providing time delay can be very effortlessly handled by using a buffer based on slow light [49].

2.6.3 Smart Antennas

Another application of slow light in radio-frequency photonics is Smart antennas also known as phased array antennas. It essentially comprises of a cluster of antennas, which can strongly enhance directional characteristics of the combined antenna by varying relative phases of the signals. Optical signals can be used to control radio services from just using one smart antenna, hence there is a need of electrical frequency dependent phase change between signals. This operation can be substituted by wavelength independent time delay through slow light [49].

2.5.4 Quantum Information Processing

For quantum information processing, quantum state is essential to be stored for some time to allow it for performing quantum operations. Now, this storing problem can be easily resolved by using slow light. Also, by slow light in quantum information processing, many other operations can be easily performed such as slowing two pulses in the same sample. The slower the light will be, the more it will get time to interact and thus close correlation state between the interacting photons and builds the basis of quantum processor [48].

3

Optical fibre

3.1 Introduction

For light to travel long distance without loss a guiding medium is required and an optical fibre is best suited for long distance lossless transmission of light. The optical fibre is a cylindrical dielectric waveguide specifically designed for light propagation. A basic optical fibre is shown in figure 10. It has 3 main parts a core, cladding and coating. Core material has higher refractive index than cladding material for propagation of light to take place. Propagation of light in an optical fibre takes place through 'Total Internal Reflection'. Let's first understand the propagation of light in a optical fibre.

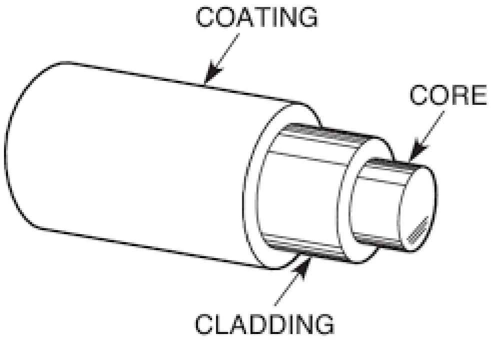


Figure 10: Basic optical fibre.

3.2 Light propagation in optical fibre

As stated earlier light propagation in a fibre takes place through total internal reflection. Total internal reflection can be defined as if the incident ray of light exceeds critical angle, the refraction would be turned into reflection. The answer to the question when will 'Total internal reflection' will happen is explained below.

- A ray of light propagating from optically rarer medium (e.g. air) to optical denser medium (e.g. water, glass) the refracted ray of light bends towards the normal/perpendicular drawn at the boundary of the two mediums in accordance with the Snell’s law. Conversely, if the ray of light propagating from optically denser to optically rarer medium the refracted ray of light bends away from the normal line.

- As the angle of incidence (θ_i) in increased for propagation from denser to rarer medium the refracted ray of light bends more away from the normal line and at a particular value of angle of incidence (based on both material refractive index) the refracted ray of light will be on the boundary as shown in figure 11. This angle of incidence is called as critical angle (θ_c).
- Now, if the angle of incidence (θ_i) is even more increased from the critical angle (θ_c) value then the refracted ray will propagate through the same denser medium with no refraction.

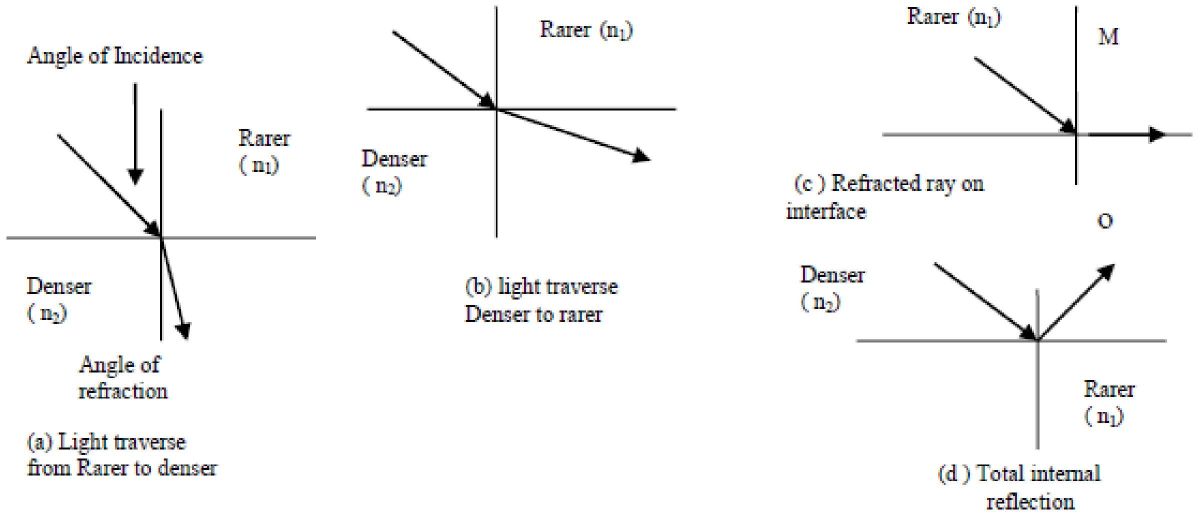


Figure 11: Total internal reflection.

So, there are some necessary conditions total internal reflection to happen in an optical fibre as explained below:

- Propagation of light must be from optically denser medium to optically rarer medium.
- The angle of incidence must be more than the critical angle so calculated for the two mediums ($\theta_i > \theta_c$).

Finding critical angle:

By using Snell’s law, we can find critical angle value as follows:

$$n_1 \sin \theta_i = n_2 \sin \theta_r \qquad \text{(From Snell's law)}$$

$$n_1 \sin \theta_c = n_2 \sin 90^0$$

$$\sin\theta_c = \frac{n_2}{n_1}$$

$$\theta_c = \sin^{-1}(\frac{n_2}{n_1})$$

3.3 Classification of optical fibres

There are many types of optical fibre present in the market. But the classification of optical fibre can be done based on three major factors as below.

- Based on material composition
- Based on refractive index profile
- Based on number of modes of propagation

3.3.1 Based on material composition

There are mainly two types of optical fibre based on material used, namely, plastic fibres and glass fibres.

Plastic fibres:

These fibres are made from polymers which have qualities like flexibility, interact less to light etc. Examples:

1. Polystyrene core; methymetha crylate cladding
2. Polymethy metha crylate core; polymer cladding

Glass fibres:

This type of fibre is made from transparent and flexible glasses as core using apt drawing methodology. Examples:

1. GeO_2-SiO_2 core; SiO_2 cladding
2. P_2O_5-SiO_2 core; SiO_2 cladding
3. SiO_2 core; P_2O_5-SiO_2 cladding

3.3.2 Based on refractive index profile

There are two types of optical fibre based on refractive index profile, namely, step index fibre and graded index fibre.

Step index fibre

In this type of fibre, refractive index of core part is constant, i.e. there is no variation in refractive index from centre of the core to core-cladding boundary. These types of fibres are known as step index fibre as there is step variation of refractive index from core to cladding as shown in figure 12.

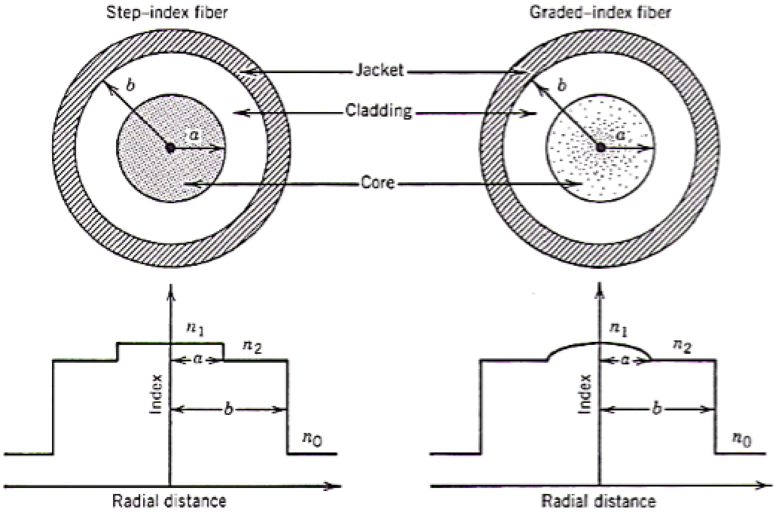


Figure 12: Step index and Graded index fibre

3.3.3 Based on number of modes of propagation

There are two types of optical fibre based on refractive index profile. They are:

1. Single mode fibres
2. Multimode fibres

Single mode fibres:

Single mode fibres are designed in a way that they can transmit only one mode or only one type of electric field distribution as shown in figure 13. Designing of single mode cause the core radius to be very less which causes fibre fabrication more difficult than the fabrication of multimode fibre.

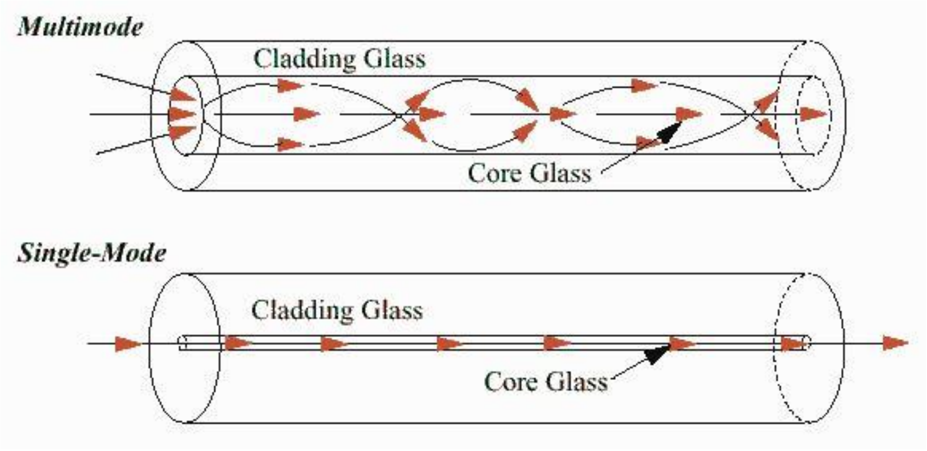


Figure 13: Single mode and multimode fibre

Multimode fibres:

Multimode fibres are a more general type of fibre, they allow multiple modes of propagation as shown in figure 13. The core radius of multimode fibre is larger than single mode fibre. A general comparison of single mode and multimode fibre is given in figure 14.

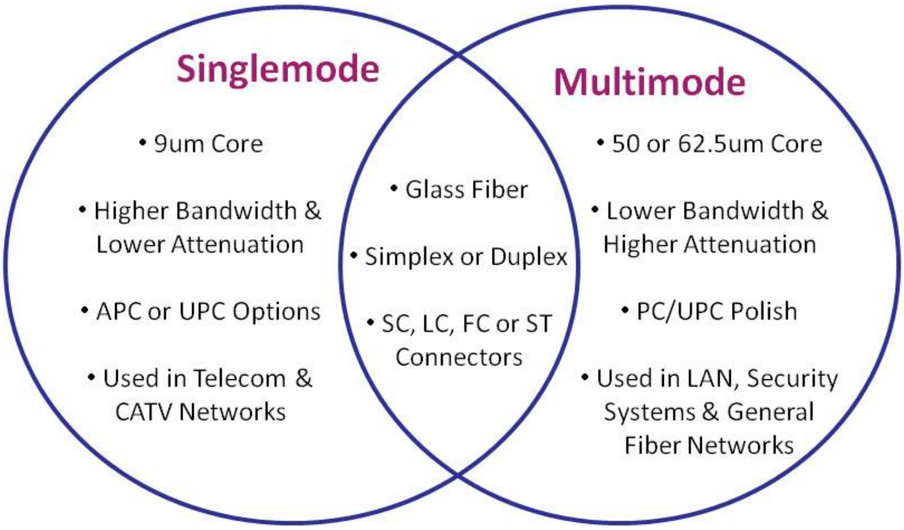


Figure 14: Comparison between Single mode and multimode fibre.

4

Modelling methods

4.1 Introduction

For carrying out modal analysis and for solution of field patterns on any design we need modelling methods. There are several techniques for solving the field problems, which we can categorise as numerical techniques experimental techniques and analytical techniques. We are using numerical techniques for our project work. The main problem hassle in using experimental techniques is that these techniques are not flexible for parameter variations and are time taking and costly. By using analytical techniques, we can obtain exact solutions, although they require high level of expertise and involve lengthy computations. Due to these hassles, we opted for numerical techniques [50] as they let the operators do the actual work although they offer only approximate solutions for the required analysis. Numerical techniques tremendous applications in solving problems in fields like electromagnetics, fluid, acoustics and heat-transfer. These techniques can be implemented using commercial software packages like COMSOL Multiphysics, RSoft etc. There are many types of numerical techniques approaches. So here in this chapter, we are explaining different numerical techniques used to solve the electromagnetic problems and which one we are using for our project.

4.2 Numerical methods

4.2.1 Finite difference method:

This a method mainly based on replacing finite difference equations in place of differential equations. This is a method based on approximations, developed by A. Thomas in 1920s. Initially, it used for solving nonlinear hydrodynamic equations. This method is now being used to solve problems in different fields.

Thus, a finite difference solution basically involves three steps:

1. Dividing the solution into grids of nodes. Some examples of grid patterns given in figure 15.

2. Approximating the given differential equation by finite difference equivalence that relates the solutions to grid points.
3. Solving the difference equations subject to the prescribed boundary conditions and/or initial conditions.

Finite difference time domain (FDTD) methodology is a time-domain numerical analysis method for resolving scattering problems. In this method, the central-difference approximation is used for resolving Maxwell’s equations for computation of the electromagnetic field patterns in depressive media of various properties for the wide range of wavelength. It's a flexible and sturdy approach for finding for advanced propagation constants. Few drawbacks of this methodology are memory complexity of the formula and laborious approach.

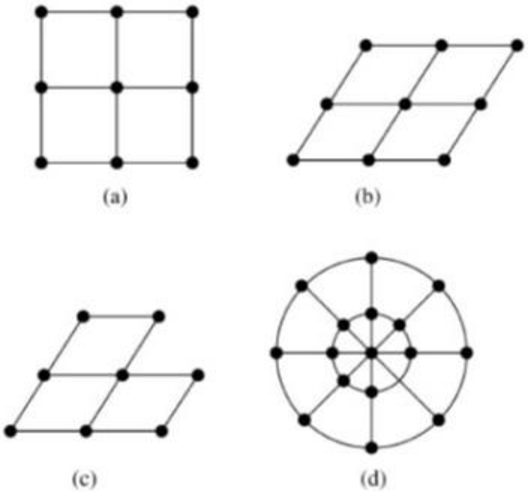


Figure 15: Common two-dimensional grid patterns.

4.2.2 Variational method:

This numerical technique offers precise results with reduced usage of computation time and system storage. In this method, the complicated drawbacks of integrating the differential equations are substituted by equivalent variational problem. Other numerical techniques like finite element method and method of moments find a base in this method. The variational problems can be resolved by selecting one of the two different approaches. The first approach is a direct method which is a classical Rayleigh-Ritz method. The second approach is called the method of weighted residuals or indirect method. The solution of a partial differential equation using the indirect variational method involves: first substituting the integral with the variational form, then selecting the suitable method to seek out the approximate solution to the problem.

4.2.3 Method of moments (MOM):

Method of moments, a general procedure for solving an inhomogeneous equation of the form $L\phi=g$, where Φ is the function to be solved, L is an operator that can be integral, differential or intro-differential and excitation function is g. It is essentially a strategy for weighted residuals. This numerical strategy might be utilized to solve different types of problems which contain scattering problems, study of lossy structures and microstrip, radiation because of thin wire elements and different problems of useful intrigue. It includes finding the weighing function and after that taking moments by multiplying with that function and then integrating. This method of solving problems utilizing this strategy involves the subsequent steps:

1. First utilizing the weighing and basis function, conversion of the derived integral equation into a matrix equation.
2. Calculation of every matrix element.
3. Lastly, getting the parameter of interests by solving the matrix equation.

4.2.4 Finite element method:

One of the most effective and versatile numerical techniques that can solve problems that include inhomogeneous media and intricate geometries and has become an important approach for all engineering disciplines. Finite element method (FEM) is considered to be a better approach than already discussed numerical techniques, despite the fact that these procedures are less demanding to program and theoretically comparative. This strategy can be connected to resolve issues in diverse regions of physics like structural analysis, electromagnetic fields, microwave waveguides, semiconductor devices, scattering analysis and so on. FEM essentially includes creating sub-domains, also known as finite elements in the given solution region.

FEM is used to find the propagation constants and the electric field distribution in the guided modes. It basically involves discretizing the solution region into sub-regions which are called finite elements. Analysing a problem using FEM technique involves few steps as described below [51]:

1. Dividing\Discretizing the region into finite no of sub-domains.

2. Solving a typical element to obtain governing equations.
3. Assembling all sub-elements to obtain the system of equations.
4. Solving the system of equations.

5

Numerical Modelling of Step-Index Optical fibre for Slow Light Generation

5.1 Introduction

Worldwide, higher data rates will be required in the coming decade and of late now the technology is shifting towards all-optical communication systems for the superior data rates possible in optical communication. But one of the roadblocks faced by an all-optical network is buffering of optical signals, creating optical memories and avoidance of electro–optical conversion. Slow light has been seen as a potential solution as discussed earlier as by using slow light phenomenon we can alter speed of light. Now as discussed in previous chapters, there are various methods to achieve slow light like stimulated Raman scattering (SRS), stimulated Brillouin scattering, electromagnetically induced transparency (EIT), coherent population oscillation (CPO), etc. We are using SBS phenomenon for our work owing to its advantages with compatibility with optical fibre communication systems, tunable working wavelength feature and room temperature operation. For our design, we have selected bismuth oxide as the core material which is highly nonlinear and high refractive index material. Also, here we are designing for single mode operation (SM) as SM waveguides are used to avoid mode competition and intermodal dispersion.

5.2 Design of optical fibre

We have designed a step index optical fibre for single mode operation for investigation of SBS-based slow light. Figure 16 shows the transverse cross-sectional view of the proposed fibre structure and figure 17 shows the fundamental mode's electric field distribution. For core, we have used bismuth oxide with diameter of 1.32 µm (d_1) and refractive index of 2.22 (n_1) with tellurite used as cladding material with a diameter of 15 µm (d_2) and refractive index of 2.03 (n_2). The PML layer is of 1µm (x) thickness. This core radius is chosen using the single mode operation condition, $V < 2.4048$.

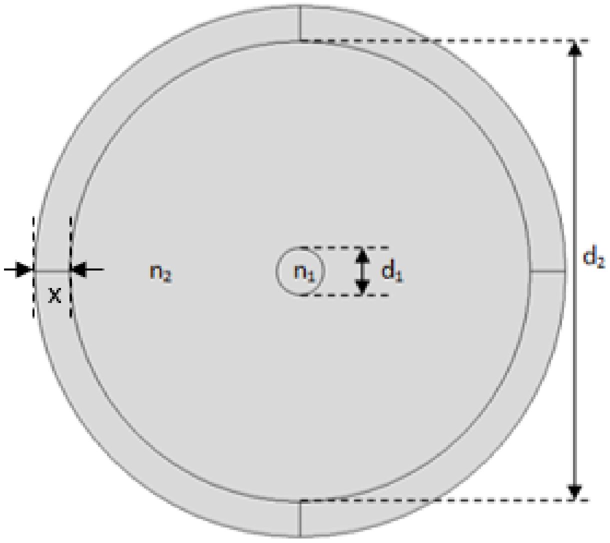


Figure 16: Transverse cross-sectional view of fibre.

$$V = \frac{2\pi \times a \times ({n_1}^2 - {n_2}^2)^{1/2}}{\lambda} \tag{5.1}$$

where V is normalized frequency parameter, a is core radius, n_1 is refractive index of core, n_2 is refractive index of cladding and λ is pump wavelength.

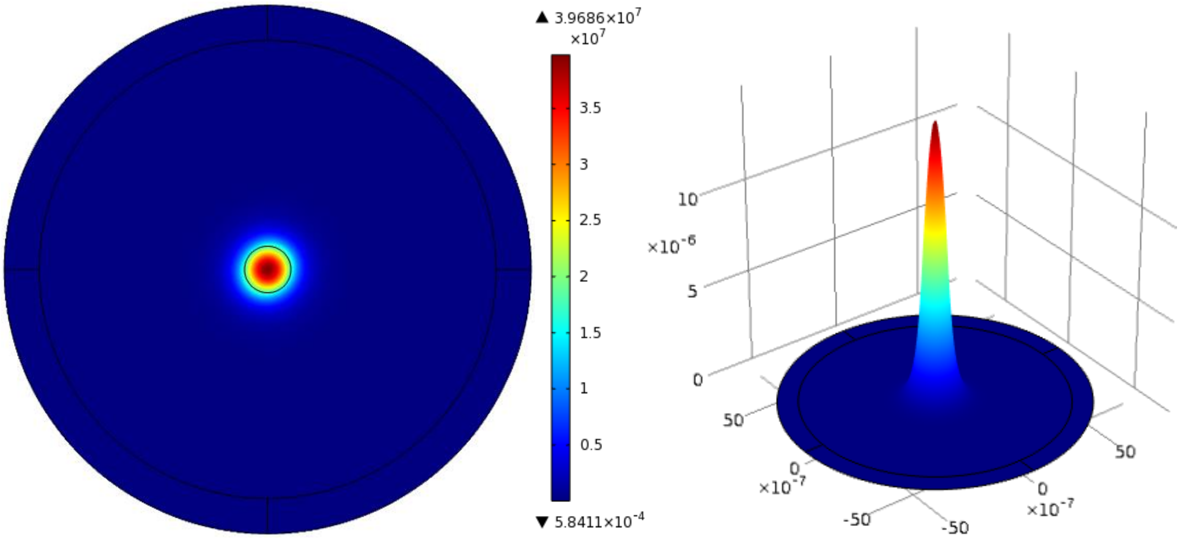


Figure 17: Fundamental mode's electric field distribution.

5.3 Simulated results and discussion

In this paper, we have simulated results for a 1 m long Bismuth oxide fibre, the inherent properties of the fibre material have been referred from [28,52]. Explicitly, refractive index of material of the core is 2.22 at 1550 nm, the Brillouin gain coefficient, $g_B = 6.43 \times 10^{-11}$ m/W, Brillouin gain bandwidth, $\Delta\nu_B$ = 32 MHz, fibre loss = 0.8 dB/m (i.e. α = 0.1842/m), Brillouin frequency shift of 8.825 GHz, and the polarization factor, K = 0.667 (as discussed earlier). By means of the above-stated parameters and the mode effective area, A_{eff} = 1.82 μm^2 for our design, we have calculated maximum permissible pump power as 976.3 mW and a corresponding time delay of 104.45 ns. Also, we calculated minimum pump power as 8.6 mW, which signifies the threshold value of pump power required to induce stimulated Brillouin scattering.

The Brillouin gain of the fibre as a function of the frequency difference between pump and signal waves has been plotted in Figure 18. For plotting this graph we have kept pump power to be constant at 500 mW. Using equation (2.12) we have calculated the frequency dependent Brillouin gain coefficient. Using this value in equation (2.14) we calculated the Brillouin gain value. In the figure, it is clearly seen that the peak gain of ~45.9 dB is obtained in this fibre at frequency shift of 8.825 GHz, which is the Brillouin shift value for bismuth oxide material. Figure 19 demonstrates the variation of Brillouin gain as a function of pump power. It is evident from this figure that the Brillouin gain linearly increases with pump power and hence, Brillouin gain can be tuned by changing pump power value.

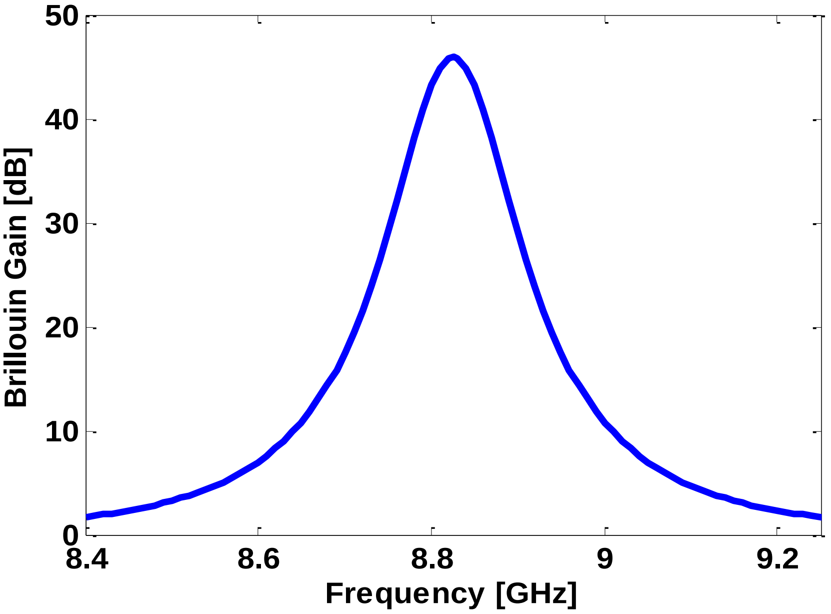


Figure 18: Brillouin gain distance as a function of frequency.

Input pump power is the utmost significant parameter in deciding the practicability of a design. In this paper, we have studied the variation of time delay with pump power. The time delay increases with increase in pump power applied on the fibre as shown in Figure 20. Thus, time delay value can be controlled by pump power value, which is the main requirement for generation of tunable slow light. The influence of fibre length on time delay per unit power (ps/mW) is illustrated in figure 21 and figure 22. The time delay per unit pump power increases with increase in real fibre length.

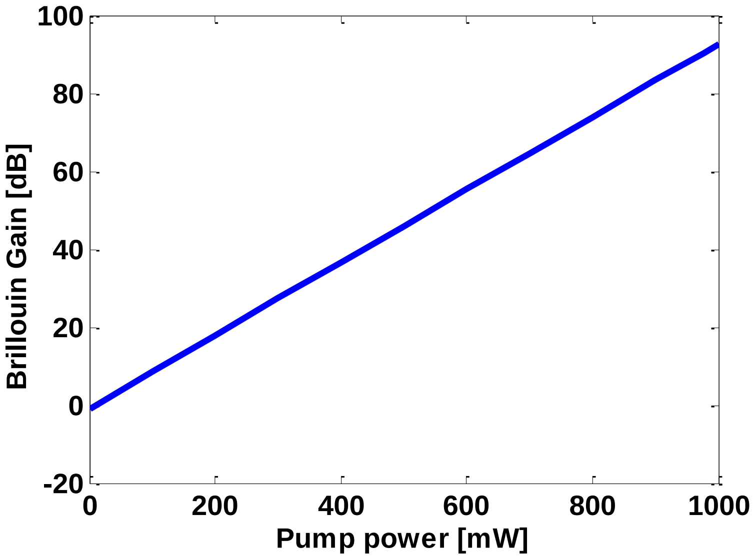


Figure 19: Brillouin gain as a function input pump power.

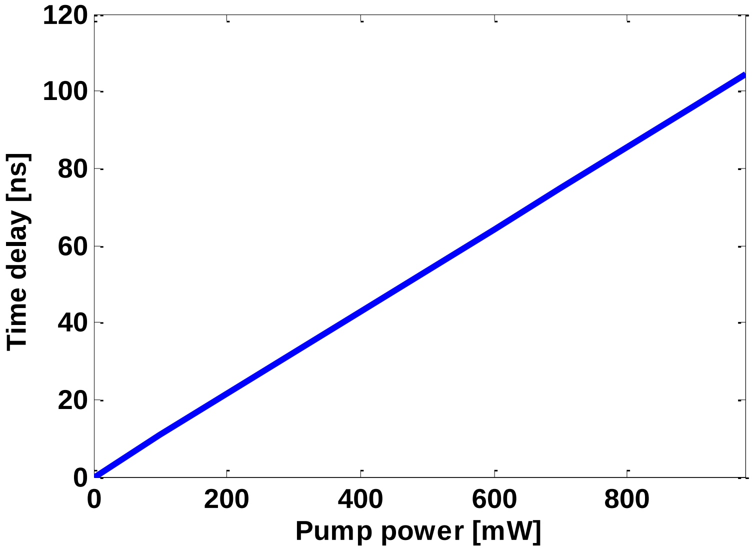


Figure 20: Time delay as a function of Pump power.

A Maximum of 90.38 dB Brillouin gain has been achieved at maximum permissible pump power of 976 mW using equations (2.14) and (2.15) respectively. Also, the minimum pump power which is required to induce SBS effect is 12.3 mW, using equation (2.16). The time delay slope efficency S_{dg} and FOM of the fibre have been calculated as 1.145 ns/dB and 45.29 respectively, using equations (2.18) and (2.19) for the pump power of 500 mW.

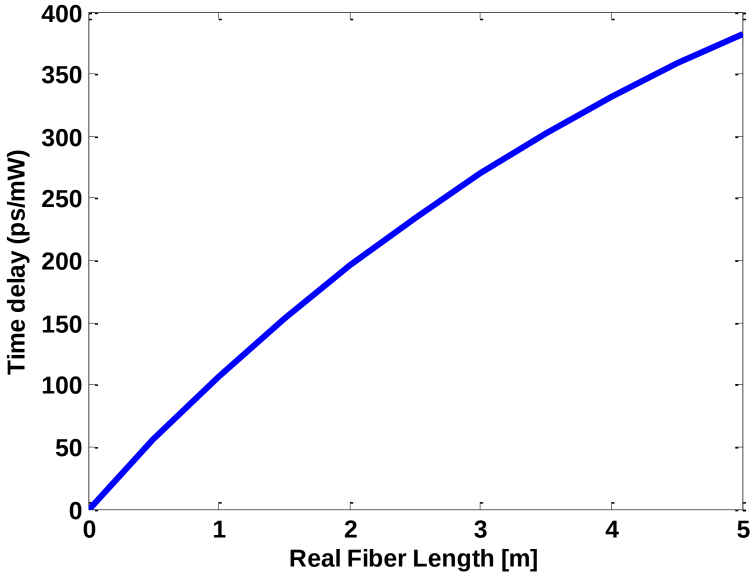


Figure 21: Time delay per unit distance as a function of Real fibre length (upto 5m).

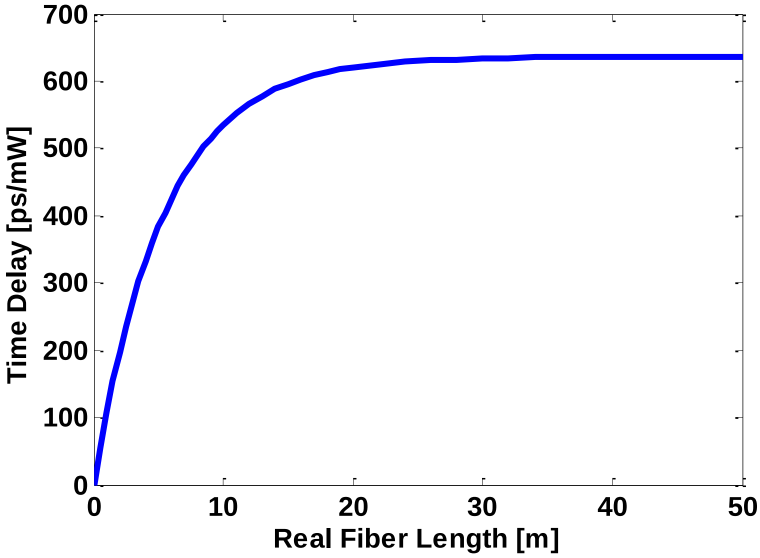


Figure 22: Time delay per unit distance as a function of Real fibre length (upto 50m).

6

Conclusion and scope for future work

6.1 Conclusion

In this project, we have numerically modelled a highly nonlinear step-index bismuth oxide optical fibre in single mode operation for slow-light generation based on the phenomenon of stimulated Brillouin scattering. To study fibre parameters such as maximum permissible pump power, time-delay, Brillouin gain, FOM and time-delay slope efficency has been simulated at a fixed wavelength of 1550 nm. For our design, an effective mode area of 1.82 μm^2 is obtained. For 1m long single mode, bismuth oxide fibre a time delay of 104.45 ns is achieved at an input pump power of 976.3 mW. Also, a Brillouin gain of 90.38 dB is achieved with a FOM of 45.29 at 500 mW of pump power. Table below provides a gist of this project with all the parameters calculated with their values.

TYPE	SPECIFICATIONS	PARAMETERS CALCULATED	
Step Index fibre (1m) for Generation of Slow Light	Single-mode operation Core – Bismuth oxide (2.22) Cladding – Tellurite (2.03) Operating wavelength – 1550nm	Effective Mode Area (μm^2)	1.82
		Maximum Time Delay Achieved (ns)	104.45
		Maximum Brillouin Gain (dB)	90.38
		Figure of merit	45.29 at 500 mW
		Time delay slope efficiency (ns/dB)	1.145

The variation of time-delay as a function of pump power and fibre length has been simulated. Also, the variation of Brillouin gain as a function of frequency and pump power is also simulated. The simulated results indicate that the time-delay in this fibre can be easily tuned with pump power as well as real length of optical fibre. Furthermore, in this project time-delay and Brillouin gain so achieved is done by using very low power which is an important parameter for real-world application of slow light.

6.2 Future Scope

Slow light based on stimulated Brillouin scattering has wide potential applications in optical communication systems. For slow light devices to become a household device we need to have parameters like large tunability range, very low power utilization by decreasing the losses and compactness of the device. Research should be done for enhancing these parameters. Integrating slow light devices with other optical devices is important for the realization of concepts like slow light engineering and chip scale optical signal processing systems.

References

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[1] Gauthier, D. J., “Slow light brings faster communication”, Physics Word 30 (2005).

[2] Krauss, T. F, “Slow light in photonic crystal waveguides”, Journal of Physics D: Applied Physics 40, 2666 – 2670 (2007).

[3] Baba, T., “Slow light in photonic crystals”, Nature Photonics 2, 465 – 473 (2008).

[4] D. J. Blumenthal, P. R. Pruncal, and J. R. Sauer, “Photonic packet switches: architectures and experimental implementations”, Proc. IEEE 82, 1650–1667, (1994).

[5] Z. Shi, R. W. Boyd, R.M. Camacho, P.K. Vudyasetu, and J.C. Howell, "Slow-light Fourier transform interferometer", Physical Review Letters 99, 240801 (2007).

[6] Z. Shi, R. W. Boyd, D.J. Gauthier, and C.C. Dudley, “Enhancing the spectral sensitivity of interferometers using slow-light media”, Optics Letters 32, 915–917 (2007).

[7] Lord Rayleigh, “On Progressive Waves", Proc. London Math. Soc., vol. 9, no. 1, pp. 21-26, 1877.

[8] J. B. Khurgin and R. S. Tucker, Eds., “Slow Light: Science and Applications (Optical Science and Engineering)”, 1st ed. CRC Press, 2008.

[9] P. W. Milonni, “Fast Light, Slow Light and Left-Handed Light (Series in Optics and Optoelectronics)”, New York: Taylor & Francis Group, 2005.

[10] L. Brillouin, “Wave Propagation and Group Velocity”, New York: Academic Press, 1960.

[11] J. Zhang, G. Hernandez, and Y. Zhu, “Slow light with cavity electromagnetically induced transparency,” Optics Letters 33, 46–48 (2008).

[12] S.-W. Chang, P. Kondratko, H. Su, and S. L. Chuang, “Slow light based on coherent population oscillation in quantum dots at room temperature,” IEEE Journal of Quantum Electronics, 43, 196–205 (2007).

[13] J. Sharping, Y. Okawachi, and A. Gaeta, "Wide bandwidth slow light using a Raman fibre amplifier," Optics Express 13, 6092–6098 (2005).

[14] E.P. Ippen and R. H. Stolen, "Stimulated Brillouin scattering in optical fibres," Applied Physics Letter, 21, 539–540 (1972).

[15] A. Kobyakov, M. Sauer, and D. Chowdhury, "Stimulated Brillouin scattering in optical fibres," Advances in Optics and Photonics, 2, 1–59 (2010).

[16] F. H. Tithi, M. S. Islam, Md. T. A. Tanna, “Overview of Stimulated Brillouin Scattering Effect and Various Types of Method to Eliminate this Effect”, International Journal of Computer Applications, 92 (7) (2014)

[17] Hau, L., Harris, S. E., Dutton, Z. & Behroozi, C. Light speed reduction to 17 metres per second in an ultracold atomic gas. Nature 397, 594– 598 (1999).

[18] M.M. Kash, V.A. Sautenkov, A.S. Zibrov, L. Hollberg, G.R.Welch, M.D. Lukin, Y. Rostovtsev, E.S. Fry, and M.O. Scully., “Ultraslow group velocity and enhanced nonlinear optical effects in a coherently driven hot atomic gas”, Physical Review Letters, 82:5229–5232 (1999).

[19] D. Budker, D. F. Kimball, S. M. Rochester, and V. V. Yashchuk., "Nonlinear magneto-optics and reduced group velocity of light in atomic vapour with slow ground state relaxation", Physical Review Letters, 83:1767–1770 (1999).

[20] M.S. Bigelow, N.L. Lepeshkin, and Robert W. Boyd., “Observation of ultraslow light propagation in a ruby cristal at room temperature”, Physical Review Letters, 90(11) (2003).

[21] T. S. Saini, A. Kumar, R.K. Sinha, "Slow light generation in single-mode tellurite fibres", Journal of Modern Optics, 62 (7), 508–513 (2015).

[22] A. Schweinsberg, N.N. Lepeshkin, M.S. Bigelow, R.W. Boyd, and S. Jarabo., "Observation of superluminal and slow light propagation in Erbium-doped optical fibre", Europhysics Letters, 73(2):218–224, (2005)

[23] C. Liu, Z. Dutton, C.H. Behroozi, and L.V. Hau.; “Observation of coherent optical information storage in an atomic medium using halted light pulses”, Nature, 409:490–493 (2001).

[24] R. Walsworth, S. Yelin, and M. Lukin; “The story behind stopped light”, Optics and Photonics News, 13(5):50–54 (2002).

[25] Schneider, T.; Hannover, D.; Junker, M.; “Investigation of Brillouin Scattering in Optical Fibers for the Generation of Millimeter Waves”, Journal of Lightwave Technology, 24, 295–304 (2006).

[26] Abedin, K.S.; "Stimulated Brillouin scattering in single-mode tellurite glass fibre", Optical Express, Vol. 14, 11766–11772 (2006).

[27] Abedin, K.S.; Lu, G.W.; Miyazaki, T.; "Slow light generation in single-mode Er-doped tellurite fibre", Electronics Letters, Vol 44, 16–17 (2008).

[28] Qin, G.; Sotobayashi, H.; Tsuchiya, M.; Mori, A.; Suzuki, T.; Ohishi, Y. J., "Stimulated Brillouin Scattering in a Single-Mode Tellurite fibre for Amplification, Lasing, and Slow Light Generation," Journal of Lightwave Technology, 26, 492–498 (2008).

[29] Kalosha, V.P.; Chen, L.; Bao, X. "Slow and fast light via SBS in optical fibres for short pulses and broadband pump", Optical Express, Vol. 14, Issue 26, pp. 12693-12703 (2006).

[30] Wang, S.H.; Ren, L.Y.; Liu, Y.; Tomita, Y. "Slow-light delay enhancement in small-core pure silica photonic crystal fibre based on Brillouin scattering" Optical Express, 16, 8067–8076, (2008).

[31] R. L. Smith, “The velocities of light," Am. J. Phys., vol. 38, no. 8, pp. 978-984, (1970).

[32] S. C. Bloch, “Eighth velocity of light," Am. J. Phys., vol. 45, no. 6, pp. 538-549, (1977).

[33] M. S. Bigelow, "Ultra-slow and superluminal light propagation in solids at room temperature," PhD dissertation, University of Rochester, Rochester, USA, (2004).

[34] Zon, X. Y., M. I. Hayee, S. M. Hwang, and A. E. Wilner, “Limitations in 10 – Gb/s WDM optical fibre transmission when using a variety of fibre types to manage dispersion and nonlinearities”, Journal of Lightwave Technology, vol. 14, 1144-1152, 1996.

[35] Scully O., “From lasers and masers to phaseonium and phasers”, Phys. Rep., 219, 191, 1992.

[36] SCULLY O., ‘Enhancement of the index of refraction via quantum coherence’, Physical Review Letters, 67, 1855, 1991.

[37] Harriss E., Field J.E., and Imamoglau, “on-linear optical processes using electromagnetically induced transparency’, Phys. Rev. Lett., 64, 1107, 1990.

[38] M. S. Bigelow, N. N. Lepeshkin, and R. W. Boyd, “Observation of ultraslow light propagation in a ruby crystal at room temperature," Phys. Rev. Lett., vol. 90, no. 11, p. 113903, (2003).

[39] A. Schweinsberg, N. N. Lepeshkin, M. S. Bigelow, R. W. Boyd, and S. Jarabo, "Observation of superluminal and slow light propagation in erbium-doped optical fibre," Europhysics Letters, vol. 73, no. 2, pp. 218-224, (2006).

[40] D. J. Gauthier, A. L. Gaeta, and R. W. Boyd, “Slow light: From basics to future prospects”, Photonics Spectra, pp. 44-50, March (2006).

[41] C. V. Raman, “A new radiation”, Indian J. Phys. 2, 387 (1928).

[42] E. J. Woodbury and W. K. Ng, “Ruby laser operation in the near IR”, Proc. IRE 50, 2347 (1962).

[43] R. K. Sinha, A. Kumar, T. S. Saini, “Analysis and design of single-mode As2Se3-chalcogenide photonic crystal fiber for generation of slow light with tunable features”, IEEE Journal of Selected Topics In Quantum Electronics, Vol. 22, No. 2 (2016).

[44] A. Tewari, T. S. Saini, A. Kumar, R. K. Sinha, “Design of As2Se3 based chalcogenide ridge waveguide for generation of slow light”, Optik - International Journal for Light and Electron Optics 127(24), 11816-11822 (2016).

[45] G. P. Agrawal, “Nonlinear Fiber Optics”, 5th ed. New York: Academic, pp. 370–385 (1995).

[46] Boyd, R.W., “Nonlinear Optics”, 3rd ed. Academic; Orlando, FL, (2008).

[47] Van Deventer, M.O.; Boot, A.J., “Polarization Properties of Stimulated Brillouin Scattering in Single-Mode Fibers”, Journal Lightwave Technology, Vol. 12, 585–590 (1994).

[48] T. F. Krauss, “Why do we need slow light?" Nature Photonics, vol. 2, no. 8, pp. 448-450, (2008).

[49] C. Chang-Hasnain, P.-C. Ku, J. Kim, and S.-L. Chuang, “Variable optical buffer using slow light in semiconductor nanostructures," Proceedings of the IEEE, vol. 91, no. 11, pp. 1884-1897, (2003).

[50] Mattew N.O. Sadiku, “Numerical Techniques in Electromagnetics”, 2nd ed., 2001.

[51] M. N. O. Sadiku, “A simple introduction to finite element analysis of electromagnetic problems”, IEEE Trans. Educ., vol. 32, no.2, May, pp. 85-89, 1989.

[52] J. H. Lee, T. Tanemura, K. Kikuchi, T. Nagashima, T. Hasegawa, S.Ohara, and N. Sugimoto, “Experimental comparison of a Kerr nonlinearity figure of merit including the stimulated Brillouin scattering threshold for state-of-art nonlinear optical fibers,” Opt. Lett., vol. 30, pp. 1698–1700 (2005).