Design and analysis of chalcogenide based waveguides for generation of slow light

A Dissertation submitted towards the partial fulfilment of the requirement for the award of degree of

Master of Technology in
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Submitted by

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CERTIFICATE

This is to certify that the work which is being presented in the dissertation entitled " **Design and analysis of chalcogenide based waveguides for generation of slow light** " is the authentic work of **Apurva Tewari** under my guidance and supervision in the partial fulfilment of requirement towards the degree of Master of Technology in Microwave and Optical Communication Engineering jointly run by Department of Applied Physics and Department of Electronics & Communication Engineering in Delhi Technological University during the 2014-16.

As per the candidate declaration this work has not been submitted elsewhere for the award of any other degree.

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ABSTRACT

A theoretical investigation of the design of a rib waveguide using highly nonlinear As_2Se_3 based chalcogenide glass has been carried out for slow light generation based on stimulated Brillouin scattering (SBS). The effective-mode-area and confinement loss of the proposed waveguide structure has been obtained for single-mode operation and their variation with the geometrical parameters has been observed. It has been found that the time delay of ~251 ns can be achieved at a pump power of 800 mW for a 10 cm long rib waveguide. Next we have designed a modified ridge waveguide with optimised parameters to obtain approximately similar time-delay with low pump power. Maximum allowable pump power and the time delay experienced by the pulse propagating in the ridge waveguide operating at a wavelength of 1.56 μm have been calculated. A maximum delay of ~249 ns has been achieved for a 10 cm long ridge waveguide at a pump power of 390 mW. It is observed that time delay can be tuned with input pump power and length of the proposed ridge waveguide. Such tunable features of the slow light can have potential applications in realization of an all-optical network.

LIST OF PUBLICATIONS

Journal Publication

- Apurva Tewari, Than Singh Saini, Ajeet Kumar, Ravindra Kumar Sinha, "Design of As_2se_3 based chalcogenide ridge waveguide for generation of slow light with tunable features" *Optik-International Journal for Light and Electron Optics*, Under Review (2016).

Conference Publication

- A.Tewari, T.S Saini, A.Kumar, "Design and analysis of As_2Se_3 based chalcogenide rib waveguide for slow light applications" Conf. Proceeding OSA Young Student Congress on Photonic Technology, MNIT Jaipur, 16-17April, 2016, OSA_YSC_104, 10-12 (2016).

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CHAPTER 1

Introduction

1.1. Thesis Approach:

This thesis consists of the design of highly non-linear, single mode chalcogenide rectangular waveguide for the generation of slow light and to study several features of the slow light based on stimulated Brillouin scattering phenomenon. All the analysis and calculations in the project are done at the wavelength of 1550 nm i.e. in the third optical window. The modal analysis of the proposed structure has been performed using commercially available software 'COMSOL Multiphysics' which is based on finite element method. The finite element method is used to calculate the effective mode area and confinement loss of the waveguide. The waveguide is studied for slow light applications and the time delay of the output pulse is calculated and its variations with different parameters of the waveguide are obtained by developing MATLAB codes. The waveguide design is modified to lower the input pump power requirements and enhancing the figure of merit of the waveguide for slow light applications.

1.2. Thesis Objectives:

The main objectives of the thesis are given as follows:

- Study of the basics of slow light, methods to achieve slow light and its applications in the optical field.
- Study and analyse the slowing down of optical signals using the non-linear effect called stimulated Brillouin scattering and study the various modelling methods used for modelling of optical waveguides.
- Design and analysis of As_2Se_3-chalcogenide rib waveguide for generation of slow light.
- Analysis of the modified As_2Se_3-chalcogenide ridge waveguide design to lower pump power requirements.
- Study the variation of time delay with pump power and other structural parameters of the waveguide to obtain tunable features.

1.3. Thesis Organisation:

The outcome of the work carried out in this project is organised in six chapters. Chapter 1 consists of the overview 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 non-linear processes in optical waveguides. Chapter 3 includes study of optical waveguides and various numerical methods for waveguide analysis. Chapter 4 deals with design of As_2Se_3- chalcogenide rib waveguide, its modelling method and its analysis for slow light applications. Chapter 5 deals with the modified As_2Se_3-chalcogenide ridge waveguide design for generation of slow light with tunable features. The project work is concluded in Chapter 6 along with the suggestions to the future work that can be done in this field.

CHAPTER 2
Understanding of the Slow Light

2.1. Introduction

The propagation of light has been a topic of study for researchers since a very long time. Rømer and Huygens were the first ones to carry out the estimation of speed of light in 1676 and 1678 using astronomical time delay observations [1]. Since then, a lot of research is being carried out to study the velocity of light [2-5]. Even in recent years, the phenomenon of speed of light is an interesting topic. Researchers are working on the reduced and accelerated speed of light. In 1877, Lord Rayleigh gave a complete description of group velocity [2]. The major breakthrough in this field happened in 1999 with the observation of dramatic reduction in the group velocity [6]. The group velocity was reduced to as low as 17 m/s, to the speed of slowly moving bicycle. This alteration in the group velocity raised several interests since then [7-9]. There has been a lot of experimental work on reducing and increasing the group velocity, or on stopping it altogether [10-20]. The negative group velocities have also been reported in non-linear optic materials [21- 23].

The alterations in the group velocity are caused by introducing non-linear optical resonances in the medium. It modifies the complex susceptibility at the vicinity of the resonance, thus dramatically changing the group velocity in several different ways, making possible the phenomenon of slow and fast light. This concept of slow and fast light came into picture from the work of Sommerfield and Brillouin in the 20th century [5]. Since then it is a topic of increasing interest. Slow light (reducing the speed of light) is a rapidly growing area in recent times because of its several applications in optical field. The ability to slow down the light has find applications in the field like optical delay lines, optical buffers, all optical memories, and non-linear optics etc. The term “slow light” basically means reducing the group velocity of light. Slow light helps in enhancing the light-matter interaction and thus replacing a bulky device into a smaller, compact structure.

A lot of work has been done in observation of slow light in optical fibers. Initially, silica-based fibers were used for generation of slow light, but to obtain suitable delay in these fibers long length of fibers (in order of kilometres) was required. *Scheinder et. al.* employed a silica-based fiber for generation of millimetre waves [24]. Later, to reduce the fiber length and to lower power requirements, materials having large Brillouin gain (g_B) were obtained. Tellurite and chalcogenide are two such materials having high non-linearity and high refractive index [25-27]. *Abedin et. al.* observed strong Stimulated Brillouin scattering in single-mode As_2Se_3 chalcogenide fiber [28] and in single-mode Tellurite fiber [29]. *Song et. al.* reported very efficient slow light generation in As_2Se_3 chalcogenide fiber [30]. *Abedin et al.* reported generation of slow light in single mode Er-doped Tellurite fiber [31]. Recently, *Saini et. al.* showed slow light generation in single-mode tellurite fibers [32]. Photonic crystal fibers have shown to be an excellent medium in slowing down light. *Yang et. al.* reported large delay slow light based on Stimulated Brillouin scattering in a short length of small-core pure silica photonic crystal fiber [33]. Recently, tunable slow light generation in photonic crystal fiber structure is reported by *Sinha et. al.*[34]. Slow light can also be achieved in optical waveguides. *Pant et. al.* reported the maximum delay of~ 23 ns for a 7 cm long chalcogenide rib waveguide [35].

2.2. Velocities of Light

Now, before studying about slow light and other alterations of the speed of light, we first need to know about the different velocities of light. When we refer to the speed of light, we are generally referring to its phase velocity in vacuum, i.e *c*. It is the speed of the constant phase front of a monochromatic light. Whenever this wave front travels inside a medium, its phase velocity decreases to an amount *c/n*, where *n* is the refractive index of the medium. This reduction in speed is not slow light. Slow light is the reduction in the group velocity of light. Group velocity is the speed of the light pulse which is the packet of several monochromatic lights travelling at slightly different frequencies. Different definitions of velocity of light have been defined [36-38]. We are defining the two most important velocities in the following section.

2.2.1. Phase velocity:

Phase velocity of a plane wave is defined as the velocity at which all the points of the wave having a constant phase travel [39]. Consider a monochromatic wave having an electric field, as a function of distance *z* and time *t*, defined as

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

Where, ω is the angular frequency of the wave, A is the amplitude, k(ω) is the wave number defined as k(ω)= ω/c×n(ω), n(ω) is the frequency dependent refractive index and it is related to the dispersion properties of the material. *c.c* is the complex conjugate term.

Here the phase of the wave is defined as,

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

For all the points having a constant phase, $d\phi/dt = 0$. Putting it in equation (2.2) we get the phase velocity, v_p, of the wave as

$$v_p = \frac{dz}{dt} = \frac{w}{k(w)} = \frac{c}{n(w)} \tag{2.3}$$

Phase velocity is a function of refractive index. This is referred to as a dispersion relation. As the refractive index of the medium increases, the phase velocity decreases and vice versa. The refractive index of most materials decreases with an increasing frequency (wavelength), causing the phase velocity to increase. This is termed as normal dispersion. However if the refractive index increases with increasing frequency, it is called as anamolous dispersion.

2.2.2. Group velocity:

If a pulse consists of a span of plane waves each having different frequency, then each frequency component (wave) will travel with its own phase velocity in the medium. The peak of the resultant wave is the point at which all the frequency component interfere constructively as shown in figure 2.1. The velocity of the result impulse is called its group velocity.

As we know, the phase of the pulse is given in equation 2.2. For the pulse to propagate without distortion it is required that there be no change in phase to the first order in ω, i.e., $d\phi/d\omega=0$. Putting it in equation 2.2, we get the group velocity of the pulse as:

$$v_g = \frac{c}{n(\omega) + \omega \frac{dn(\omega)}{d\omega}} = \frac{d\omega}{dk} \tag{2.4}$$

We can also write $v_g=c/n_g$, where n_g is the refractive index given as :

$$n_g = n(\omega) + \omega \frac{dn(\omega)}{d\omega} \tag{2.5}$$

The second term in this equation is the measure of dispersion. If $dn/d\omega$ is positive, then the group refractive index increases with ω. This is called as normal dispersion and if this value is negative, then it is referred to as anomalous dispersion.

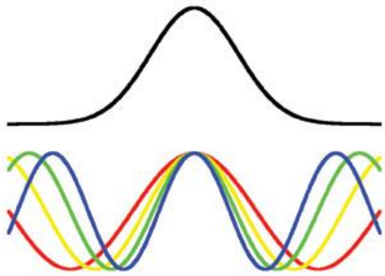


Fig2.1: *Sinusoidal component waves interfere to create a pulse of light.*

In the optical regime, the value of ω is quite large, thus even if there is a slight increase in the magnitude of the dispersion the group refractive index increases to a large amount and thus reducing the group velocity astonishingly. This is the theory behind the slow light in optical medium. This alterable behaviour of the group velocity in optical medium can be used to engineer structures with large externally controllable dispersion.

2.3. What is the Slow Light?

As discussed earlier, slow light is the propagation of an optical pulse at a very low group velocity. Although the ultra high speed of light, with which it travels in vacuum, has a great advantage in the field like communication for the transmission of data from one point to another. However, at such high speeds it is very difficult to control the light. Thus to have a better control over it, there is a need of "slow light". Slow light has become a topic of increasing interest in the recent years, because of its huge practical potential, along with the fundamental physical interests. An all-optical network without the need of any O-E-O conversions could reduce the size of optical devices considerably smaller, along with reducing lot of energy requirements. Also, the requirements of high bandwidth internet services also rely on all-optical networks. All this can be achieved by slowing down the light to a considerable amount. Thus slow light is a backbone of communications and information systems [40, 41]. Slow light also has applications in signal processing. It helps in increasing signal bandwidth and carrier frequencies without incurring any significant losses. Slow light also has numerous potential applications in optical information processing, such as optical data storage, quantum computing, optical memories, optical communication systems, data synchronization and optical buffering [42-44]. On-chip all-optical processing of signals with less wasted heat is possible by storing the light and enhancing the nonlinearity.

Slow is achieved in a non-linear medium by tailoring the dispersion in a narrow spectral resonance. As explained in the previous section, to generate slow light effect in the medium it is necessary to introduce a large change in refractive index with respect to frequency in the narrow spectral region. When the different frequency components of the optical signal travel inside such medium, they travel with different velocities, thus causing a significant change in the group velocity. This significant reduction in group velocity is referred to as slow light and the increase in it is called fast light. In the normal dispersive medium where the group velocity is less than phase velocity, the energy density in the medium is inversely proportional to the group velocity of light. This is done to maintain the conservation of energy. This way the group velocity controls the flow of photons. This is shown in figure 2 below that the intensity of light is enhances by squeezing the spatial pulse length.

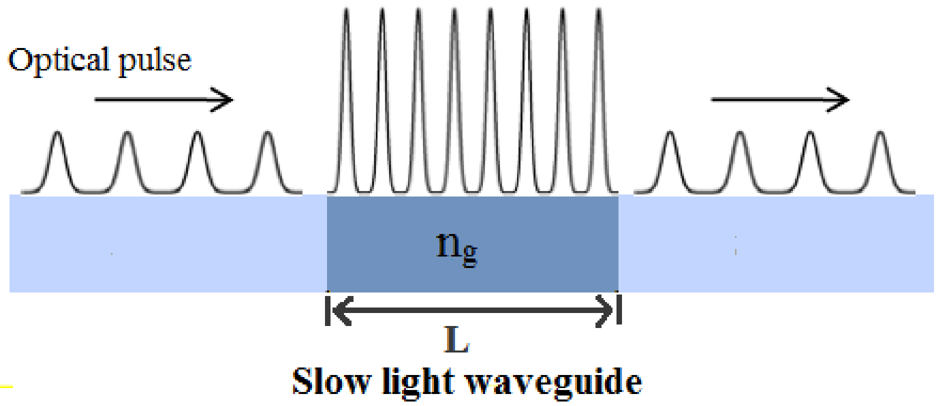


Fig. 2.2: *Schematic diagram of a pulse entering a slow light waveguide*

As shown in figure 2.2, the optical pulse is passed through a non-linear medium having length *L*. It experiences a slow light effect in the medium due to its dispersion properties. The time taken by the signal to pass the medium is called group delay, given by:

$$T_g = \frac{L}{v_g} = \frac{Ln_g}{c} \tag{2.6}$$

For the signal to achieve large delay, it is required to have a large group refractive index change in a narrow spectral region. It can be achieved by introducing a strong dispersion in the medium in the vicinity of resonance. This cause group velocity to decrease, thus a large tunable delay is achieved.

2.3.1. Methods to achieve slow light

This section gives an overview of different approaches to achieve slow light. As mentioned earlier, slow light is an inter-disciplinary topic and thus it deals with a vast variety of methods for slow light generation. However there are two basic classifications of these methods, one called the microscopic approach and other macroscopic approach. In the following paragraph, we study about these two approaches in detail and various methods under these approaches.

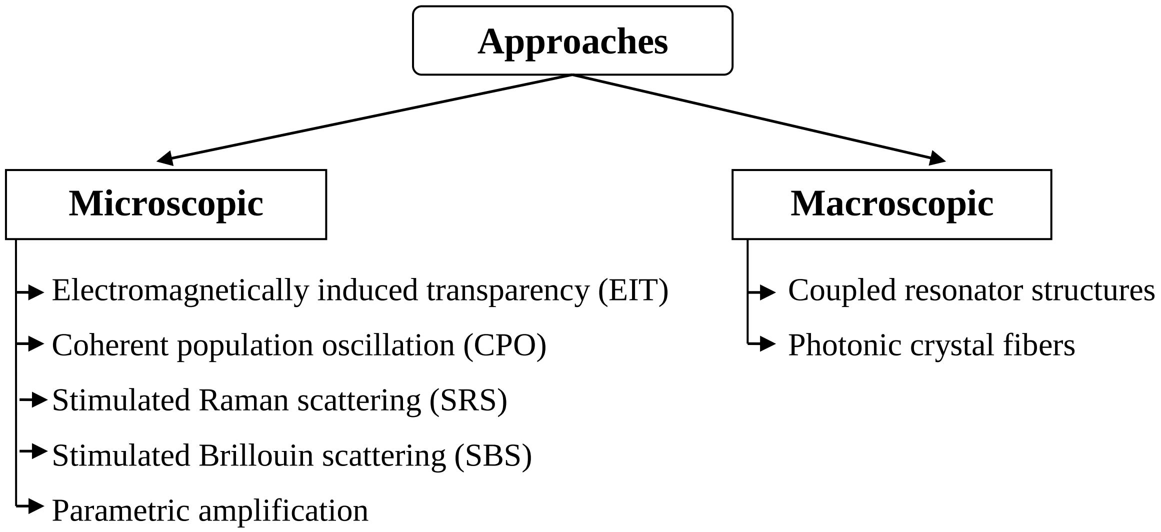


Fig 2.3: *Different methods to achieve slow light*

Microscopic approach to generate slow light involves those processes in which the group index changes mainly because of the interaction of light and matter at the atom or molecule level. They are based on material resonances. On the other hand, macroscopic approach of slow light generation is basically based on material structure. It includes the processes in which the change in the group velocity is contributed to the interaction of light with structural geometry of the material, and the structural geometry is of the order of optical wavelength.

2.3.1.1. Microscopic approach

Since for slow-light medium, group index has a strong dependence on the term '$\omega dn/d\omega$', that means, this quantity can significantly affect the group index. Now, refractive index n(ω) and absorption coefficient α(ω) are dependent on susceptibility of the medium χ(ω), where susceptibility denotes the degree to which a material may be polarised in an electric field. This is given by:

$$P = \varepsilon_o \chi E \qquad (2.7)$$

Where, ε_o denotes permittivity of free space and E denotes electric field strength.

Also,

$$n(\omega) = Re\{\sqrt{\varepsilon_r}\} = Re\left\{\sqrt{1+\chi(\omega)}\right\} \qquad (2.8)$$

$$\alpha(\omega) = \frac{2\omega}{c} Im\{\sqrt{\varepsilon_r}\} = \frac{2\omega}{c} Im\left\{\sqrt{1+\chi(\omega)}\right\} \quad (2.9)$$

Here, $\varepsilon_r = 1+ \chi(\omega)$. It is the permittivity of the medium. Kramers and Kronig has given the relation between the real and imaginary part of susceptibility [45]. These equations are famously called Kramers-kronig relations (KKR). These relations have given some important conclusions. Firstly, material exhibiting absorption must also possess dispersion and conversely, the spectral variation in the absorption has to be present in a dispersive medium. It can also be derived that the real and imaginary parts of the complex refractive index satisfy the Kramers-Kronig relations [46]. Thus, at the vicinity of some absorption or gain resonances, large dispersion of $\omega dn/d\omega$ occurs.

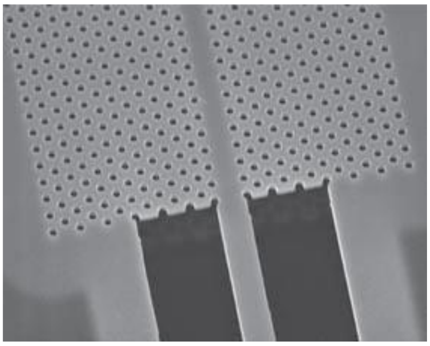
Some slow light methods use this approach of introducing absorption or gain resonances to attain large dispersion in the medium. This approach is called microscopic approach. There are several methods that use this feature of material resonance for achieving slow light effect. Coherent population oscillations (CPO) [47], electromagnetically induced transparency (EIT) [48], parametric amplification [49], Stimulated Raman scattering (SRS) [50], and Stimulated Brillouin scattering (SBS) [51, 52] are some of these microscopic methods.

2.3.1.2. Macroscopic approach

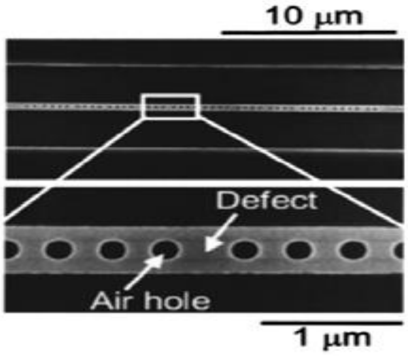
As mentioned earlier, the macroscopic approach of slow light generation involves the interaction of light with the structural geometry of the element in the medium. The geometry of the element is equal or larger than the wavelength of the light wave. This slow light effect is mostly based on the material structure. It can also be explained using the concept of waveguide dispersion.

Light entering the optical waveguide is mostly guided in the core of the waveguide; however, a small fraction of the energy in the propagating mode is leaked into the cladding. The ratio of the energy guided in the core to that in the cladding is the parameter on which effective refractive index of the propagating mode depends. This ratio changes for different wavelengths, thus the effective index also varies with the frequency. The dispersion that we get due to this variation is the intramodal or intermodal waveguide dispersion. In typical optical waveguides, this dispersion is not large enough to experience any slow light effect. However, if we modify the structure of the waveguides such that there is a large variation of index with the frequency and thus in return getting greatly enhanced waveguide dispersion, we can achieve slow light effect. This approach of slow light generation is called the macroscopic approach.

These novel structures based on macroscopic slow light include coupled resonator optical waveguide (CROW), Photonic bandgap structures, fiber or waveguide structures etc. Some of these structures are shown in fig 2.4 below. Photonic crystal structures basically have periodical patterning of dielectric media. Photonic crystals are so called because they have a similarity to a crystal lattice in a solid material. Photonic crystals have a discrete translational symmetry in its structures. This symmetry is responsible to strong dispersive properties in it, which contributes to slow light effect in photonic crystals.



(a)



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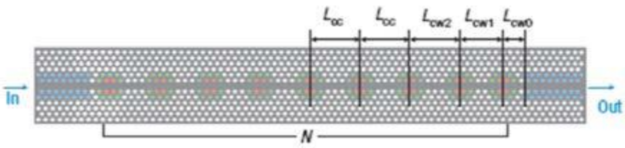


(c)

Fig2.4: Various types of macroscopic slow-light structures. (a) Photonic crystal waveguide [53]. (b-c) coupled-resonators optical waveguides (b) based on silicon grating resonators [54] (c) photonic crystal resonators [55].

2.3.2. Applications of the slow light

Researchers have found slow light as an excellent method to conduct several interesting studies of fundamentals of propagation of light. Along with that, slow light also has several exciting potential practical applications. The applications of slow light have been inter-disciplinary, covering various different areas like communications, optical signal processing, quantum optics, spectroscopy and RF photonics. However the applications can basically be clubbed into three categories: tunable optical delay lines, enhancement of non-linearity, and interferometry.

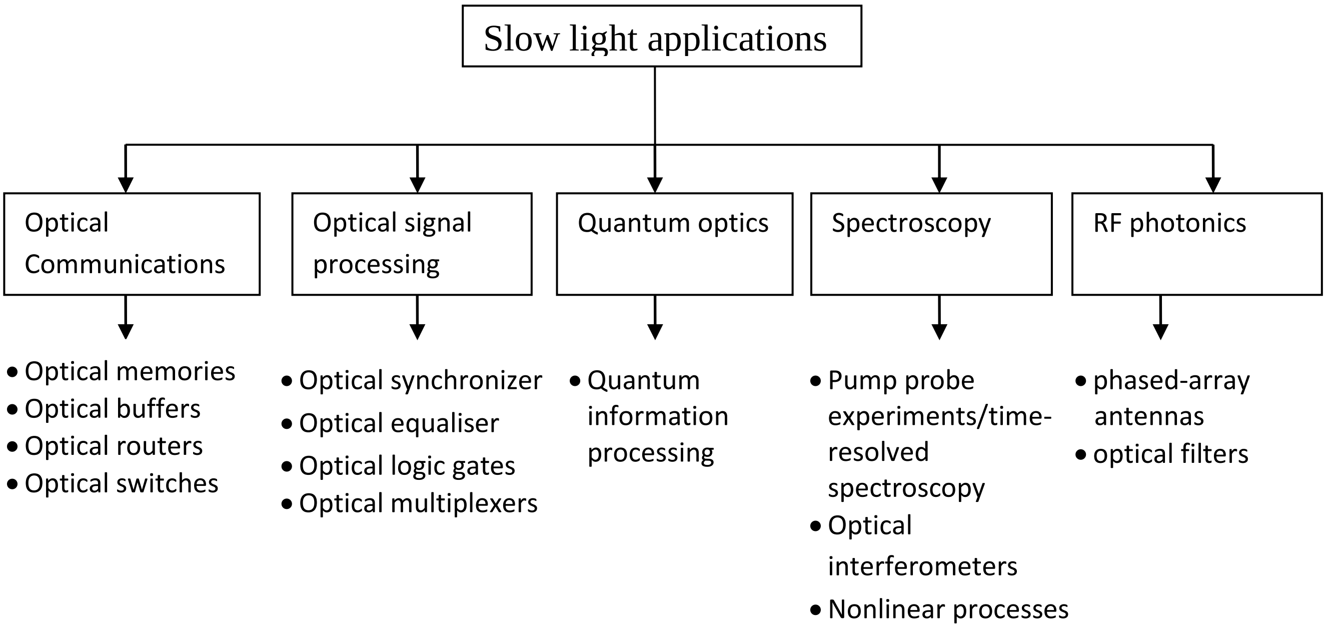


Fig2.5: *Applications of slow light in different fields.*

2.3.2.1. Tunable optical delay lines:

Tunable optical delay line is perhaps the most obvious application of slow light. They are basically small devices that can buffer or store optical pulses for considerable amount of time. The time taken by an optical pulse to propagate through the slow light medium can be controlled as we are able to control its group index. These all-optical controllable delay lines can be of use in various fields. In the field of optics communication, it has applications like data resynchronisation, optical buffering, jitter correction, etc. RF photonics [56], optical signal processing [57], and slow-light laser radar are some other fields where all-optical tunable delay lines are used.

Optical delay lines have been proposed to be used in optical routers. These routers would be used to create an all-optical network that could increase the performance of communication networks [58]. At present times, electric routers are used, that means to perform routing functions there is a need to convert optical signals to electrical and then back to optical after processing. This OEO conversion requires additional power in the transmission along with adding delay to the network.

2.3.2.2. Enhancement of optical nonlinearities:

Optical nonlinearities can be generated and enhanced using the slow light effect. Generally, there is a requirement of large interaction time and length with the medium and high optical powers for generation of nonlinear processes in non-slow light medium. This implies expensive and large equipments are required for generating nonlinearities. Since slow light effect increases the optical intensity inside the medium, thus a higher strength of nonlinear interaction [59]. This feature of slow light causes low optical power requirements for efficient nonlinear generation, thus enabling use of inexpensive equipments and miniaturization of devices.

In optical communication, enhanced nonlinear interaction has another application – the optical regenerator. Regenerator is a device that recreates the signal removing any distortion or noise that might have added into the signal while propagating over a long distance. Regenerator uses the principle of optical transfer function. In present times, this process of regeneration is costly, requiring high optical powers. So mostly electric regenerators are used instead of optical regenerators, but they require optical-electrical-optical (OEO) conversion. The slow light effect could, however, as explained earlier could reduce the power and cost, thus optical regenerators could be made possible [59, 60]. Slow light effect finds another application for nonlinear optics in improving the phase matching condition. It can be achieved by delaying or accelerating various optical channels. It was demonstrated how the Brillouin slow light effect in optical fibers is used in FWM processes to obtain all optical control of phase-matching conditions [61].

2.3.2.3. Slow light interferometry:

As we know that the refractive index of the medium in the slow light effect is a function of frequency [62]. This implies, a slight deviation in the frequency can affect the wave number in a large way. This property of slow light has lead to another application in the field of spectroscopy. The performance of spectroscopic interferometers can be enhanced using the spectral properties of slow light. In such interferometers, placing a slow light medium can increase the frequency sensitivity of one path by a factor of the group refractive index [63]. This causes the change in the optical path difference between the two paths in interferometers. Effect of introducing slow light in Mach-Zehnder interferometer is shown in figure below. The similar effect of slow light in sensitivity can also be observed in Fabry-Perot cavity, where the linewidth of cavity is changed [64]. Further, Interferometric rotation sensing [65, 66] and Fourier-transform interferometry [67] have also been proposed to use slow light effect.

2.4. Stimulated Brillouin Scattering

2.4.1. Non-linear processes in optical waveguide

Light wave entering the optical waveguide is mostly linear, i.e. the polarisation *P(t)* of the incident light is proportional to its electric field *E(t)*, as given by,

$$P(t) = \varepsilon_o \chi E(t) \quad (2.10)$$

Where, ε_o is the permittivity of vacuum, χ is the linear susceptibility. This is known as linear polarisation. However, if the small core area of optical waveguide confines a high intensity light wave, the light-matter interaction becomes non-linear. The polarisation relation deviates from the simple linear relation, it now also include higher order terms of electric field [45]. These higher order terms result in the non-linear optical processes. Now polarisation is given as:

$$P(t) = \varepsilon_o (\chi_1 E(t) + \chi_2 E(t)^2 + \chi_3 E(t)^3 + \ldots\ldots\ldots\ldots) \quad (2.11)$$

Here, χ_2 and χ_3 are second and third order susceptibilities.

Non-linear response is fundamentally associated with the "anharmonic motion of bound electrons due to interaction with the applied field". In optics, the term 'non-linear' basically means intensity-dependence of refractive index. In non-linear optics, the output light wave does not linear depend on the input, as explained from the graph below [68]:

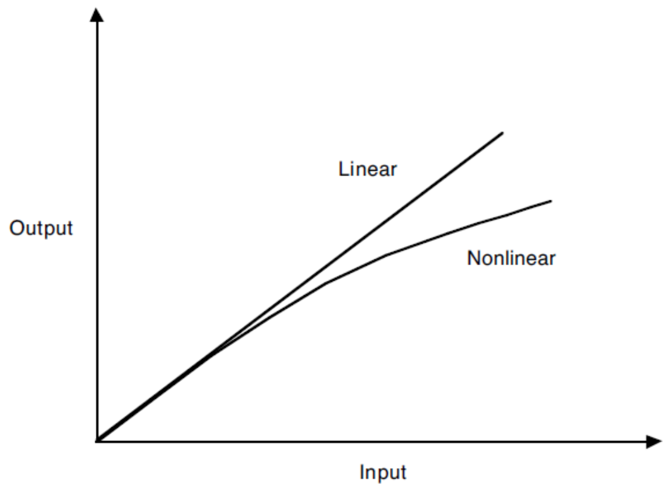


Fig2.6: *Linear and non-linear interaction in optical waveguides.*

(taken from ref [68])

The non-linear effects are mostly related to non-linear refraction which is given by,

$$n(\omega, I) = n(\omega) + n_2 I = n(\omega) + n_2 |E|^2 \quad (2.12)$$

The first term *n(ω)* is the linear part, n_2 is the non-linear index coefficient. It is related to the third order susceptibility as:

$$n_2 = \frac{3}{8n} Re(\chi_3) \tag{2.13}$$

Here, *Re* means the real part of susceptibility, n is the linear refractive index. The non-linear effect in optics basically occurs due to two reasons. Firstly, due to variation in refractive index due to intensity, and secondly due to inelastic scattering phenomenon. Self Phase Modulation (SPM), Cross Phase modulation (CPM), and Four Wave Mixing (FWM) are some of the non-linear effects that occur due to intensity dependence of refractive index. The inelastic scattering phenomenon generates effects like Stimulated Brillouin scattering (SBS) and Stimulated Raman scattering (SRS). Non linear effects can majorly impact the propagation of light in optical waveguides. Though these effects are detrimental to optical transmission, they enable some new functionalities which have great benefits in various fields of optics. Some of these phenomenons are slow light, supercontinuum generation, wavelength conversion etc.

2.4.2. Physical processes of the SBS

Stimulated Brillouin scattering (SBS) is an efficient non-linear method because it is compatible with optical fiber communication systems, operates at room temperature and has tunable working wavelength. It is a third order non-linear effect in which the light incident to an optical waveguide scatters in the backward direction. It involves the generation of Stokes wave, which travels in the backward direction and carries most of the input power, after reaching a certain threshold. The scattering of light by acoustic waves was first investigated by the French scientist Leon Brillouin in 1920s. However, it was not until the invention of laser source in 1960s that Brillouin scattering gained attention, since high intensity light is required to achieve large scattering.

SBS is basically a nonlinear process in which the pump, Stokes and an acoustic wave interact through the electrostriction process [45]. Acoustic wave is initially thermally generated and it produces density modulations in the medium, which causes variations in the refractive index producing index grating. This grating causes the incident pump wave to scatter through the process of Bragg diffraction. The scattered light experiences the Doppler shift (caused by the grating), due to which there is a downshift of frequency in the scattered light. In terms of quantum mechanics, this process can be viewed as if a Stokes photon and an acoustic phonon are created due to the annihilation of a pump photon. Let ω_p and ω_s are the frequencies; and k_P and k_S are the wave vectors of pump and Stokes wave respectively. Since for each scattering event, the energy and momentum must be conserved, we can define the relation of the three waves as:

$$\Omega_B = \omega_P - \omega_S; \; k_A = k_P - k_S \tag{2.14}$$

Where, Ω_B and k_A is the frequency and wave vector of acoustic phonon, respectively. They are related using the dispersion relation as,

$$\Omega_{\boldsymbol{B}} = v_A|k_A| \approx 2v_A|k_P|\sin(\theta/2) \tag{2.15}$$

Here, v_A is the acoustic velocity and θ is the angle between the Stokes and pump wave. We have also assumed that k_P and k_S are approximately same. It can be seen that the frequency of acoustic phonon depends on the scattering angle. It implies that the frequency shift in the Stokes wave is maximum when θ=π, i.e. in the backward direction, and zero when θ=0, i.e. in the forward direction. This is the reason why SBS effect occurs only in backward direction in optical waveguides. Brillouin gain spectrum is a Lorentzian gain curve that defines the growth of the Stokes wave, which has a peak at the acoustic frequency, Ω_B.

2.4.3. Theory of SBS based slow light

SBS based approach is very practical and feasible technique for slow-light-based devices because of its wavelength independent nature, large signal bandwidth range (MHz to GHz), and possibility to control the pulse delay all optically only by tuning the pump power [69-71]. This section deals with how SBS process generates slow light in optical waveguide.

SBS is a nonlinear process in which the light incident to an optical waveguide scatters in the backward direction. This backward scattering can be used for amplification of the signal travelling in the direction opposite to the pump. The high intense pump wave is made to interact with the counter propagating weak signal wave resulting in the generation of slow travelling intensity wave which causes travelling density variations (variations in the refractive index) in the medium. This wave is called the acoustic wave. This occurs when the travelling intensity wave has the frequency equal to the difference between the frequencies of the pump wave and signal wave. The travelling refractive index grating can cause coupling of power between pump and signal waves at phase matching condition. The grating diffracts the light from the higher frequency pump wave to the weak signal wave, which as a result, experiences a gain.

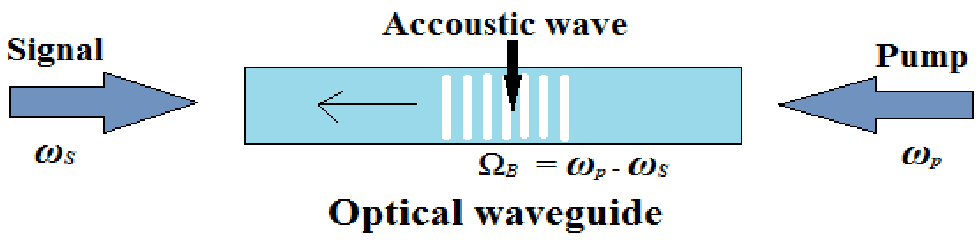


Fig2.7: *Schematic of the principle of stimulated Brillouin scattering in optical waveguide.*

Let ω_P and ω_S are the frequencies of pump wave and signal wave, respectively and I_p and I_s their intensities. Phase matching condition states that the difference in their frequencies should be equal to the brillouin frequency shift (Ω_B), i.e., $\omega_P - \omega_S = \Omega_B$. The signal frequency is much smaller than pump frequency.

The coupled nonlinear differential equations for the pump and the signal waves are given by the equations below [72]

$$\frac{dI_P}{dZ} = -g_B I_P I_S - \alpha_P I_p \tag{2.16}$$

$$-\frac{dI_s}{dZ} = +g_B I_P I_S - \alpha_S I_s \tag{2.17}$$

where, g_B is the Brillouin gain coefficient, α_P and α_S are material losses at pump and signal frequencies, respectively. If we assume that the pump wave is undepleted, then $\alpha_P = \alpha_S = \alpha$, thus the solution to the above equations is given by

$$I_s(0) = I_s(L)\exp\left(\frac{g_B P_p L_{eff}}{A_{eff}} - \alpha L\right) \tag{2.18}$$

Here, P_p is the input pump power, A_{eff} is the effective-mode-area of the propagating mode, α is the attenuation constant of the waveguide, L is the real length of waveguide and L_{eff} is the effective length of waveguide which is given by the equation 2.19 below.

$$L_{eff} = \frac{[1 - \exp(-\alpha L)]}{\alpha} \tag{2.19}$$

Effective-mode-area, A_{eff} is defined as

$$A_{eff} = \frac{(\iint_{-\infty}^{\infty} |E|^2\, dx\, dy)^2}{(\iint_{-\infty}^{\infty} |E|^4\, dx\, dy)} \tag{2.20}$$

where, E denotes electric field distribution in the waveguide. The Brillouin gain coefficient is defined as

$$g_B(\Omega) = \frac{g_p\left(\frac{\tau_B}{2}\right)^2}{(\Omega - \Omega_B)^2 + \left(\frac{\tau_B}{2}\right)^2} \tag{2.21}$$

Here, g_p is the maximum value of the gain at $\Omega = \Omega_B$ and is given by

$$g_p = \frac{2\pi n^7 {p_{12}}^2}{c{\lambda_P}^2 \nu_A \Delta\nu_B} \tag{2.22}$$

where, n is the refractive index of the material used in waveguide, p_{12} is the longitudinal elasto-optic coefficient, c is the velocity of light in free space, λ_P is wavelength of the pump wave, v_A is the acoustic velocity, and Δv_B is the Brillouin gain bandwidth. Non-linear parameter is calculated using the formula

$$\gamma = \frac{2\pi n_2}{\lambda A_{eff}}$$

Where, n_2 is the non-linear refractive index of the material. We require a minimum pump power to initiate the SBS effect. It is when the brillouin gain is larger than the losses of the waveguide, and is given by

$$P_{min} = \frac{\alpha A_{eff} L}{K g_B L_{eff}} \tag{2.23}$$

Also, there is a maximum power above which the output signal gets distorted. When the pump power reaches this maximum allowable power, the backscattered waves are generated from the background noises in the waveguide which leads to output signal distortion. It is given by the following relation [31]

$$P_{max} = 21 \frac{A_{eff}}{K\, g_B L_{eff}} \tag{2.24}$$

where, K is the polarization factor, the polarisation properties of the waveguide decides its value. If the polarization is maintained, its value is 1, and it is 0 if not maintained. It is shown from some results that $K = 0.667$ is an appropriate value for low birefringence waveguide with high polarization beat length [31, 73]. The time-delay per unit length per unit pump power induced due to SBS effect in the slow light devices is expressed as [70]

$$\frac{\Delta t_d}{P_p L_{eff}} = \frac{g_B K}{\tau_B} \tag{2.25}$$

Here, τ_B is the Brillouin line width ($\tau_B = 2\pi\Delta\nu_B$, where $\Delta\nu_B$ is the Brillouin gain bandwidth as mentioned above) [74]. Brillouin gain is an another parameter which depends on the input pump power and it is expressed as [75]

$$\text{Gain [dB]} = 10\log(\exp\left(g_B K \left(\frac{P_p}{A_{eff}}\right) L_{eff}\right) - \alpha L \tag{2.26}$$

Theoretical value of the gain is given by

$$\mathrm{G_{th}} = 4.34\left(\frac{\mathrm{g_B K \times 1mW \times L_{eff}}}{\mathrm{A_{eff}}}\right) \tag{2.27}$$

Another important parameter that defines the suitability of waveguide to be used as a slow light medium is figure of merit (FOM). It is defined as [30]

$$FOM = \frac{Gain[dB]}{P_p L_{eff} n} = 4.34\left(\frac{g_B K L_{eff}}{A_{eff} n L}\right) \tag{2.28}$$

CHAPTER 3
Optical Waveguides and its Modelling Methods

3.1. Introduction

The field of integrated optics emerged in late 1960's [76] which replaced the electrical wires and radio links with light guiding optical fibers, and electronic integrated circuits by miniaturized optical integrated circuits. This approach of integrated optics offers significant advantage in signal processing and transmission in terms of cost as well as performance. Thus the fabrication of optical waveguides has gained much attention because of the broad scope in integrated optics. Guided wave optics has several applications, be it in terms of optical fibers or in planar technologies. Optical fibers are the fundamental backbone of telecommunication networks, also used for high speed computer interconnects, in medical and manufacturing laser applications. Planar optical waveguides find applications in production of amplifiers and lasers, in modern sensor and measurement systems. They also have potential in production of compact optical components at very low cost.

It is a difficult process to examine electric field in a waveguide and special mathematical knowledge is required for its calculation. To calculate parameters like mode field distribution and the propagation constant, we need to analyse the guiding of light in optical waveguides. There are different approaches to mathematically analyse the waveguide, like analytical approach, numerical approach etc. These methods are very important for modelling of optical waveguides to study different phenomenon of light propagation in waveguide. In this chapter, we have given theoretical details of optical waveguides, their types and guiding mechanisms. Then we have discussed the methods used for analysis of these waveguides.

3.2. Optical Waveguides

Optical waveguides are physical structures that guide and transmit electromagnetic waves in the direction parallel to their axis. The electromagnetic waves are in the optical spectrum. The optical waves are mostly guided using total internal reflection (TIR), in which the light is confined in the high index material and bounces on the interfaces with lower index material. Figure 3.1 shows the optical waveguide in rectangular coordinate system abruptly terminated by the dielectric discontinuity. The lateral dimensions of these waveguides are in the range of nanometre or micrometre. They comparatively have very large longitudinal dimensions ranging upto 100,000's of wavelength. These waveguides are building blocks of various optical devices like fiber amplifiers, fiber lasers and all-optical photonic integrated circuits. They are also used as the transmission medium in optical systems like fiber optics communications. These optical waveguides can be analysed by solving Maxwell's equations:

$$\Delta \times E = -\frac{\partial B}{\partial t} \tag{3.1}$$

$$\Delta \times H = \frac{\partial D}{\partial t} + J \tag{3.2}$$

$$\Delta . D = \rho \tag{3.3}$$

$$\Delta . B = 0 \tag{3.4}$$

Here, B and D are the electric and magnetic flux densities, E and H are the electric and magnetic fields, ρ is the electric charge and J is electric current densities. Applying these electromagnetic wave equations with appropriate boundary conditions based on the material of core and cladding, and on the properties of waveguide, determines the characteristics of the light travelling in the waveguide.

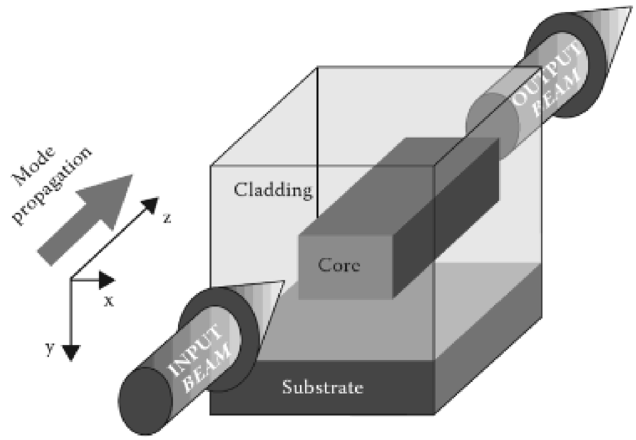


Fig 3.1: *Light propagating in optical waveguide. (Taken from ref. [77])*

3.2.1. Classification

This section briefly describes several optical waveguides that are used in photonic devices and integrated optics. The functional elements of integrated optical circuits require optical waveguides that provide optical confinement in the transverse direction. Photonic devices use optical waveguides that meet the certain design specifications using a selected fabrication technique and device applications. There are several different ways in which we can classify optical waveguides. An optical waveguide may be classified based on:

- waveguide geometry: planar and non-planar waveguides
- guiding mechanism: total internal reflection, photonic bandgap, antiguiding, and antiresonant guiding etc.
- mode structure: single-mode or multi-mode,
- material used: semiconductor, glass, polymer, metal, artificially created materials.

On the basis of geometry, optical waveguides are of two types, planar and non-planar. The planar waveguides are the ones that provide confinement of light in only one transverse direction, say *x*. In this the cladding layers surround the core in only one direction. The core is called the film of the waveguide, which is sandwiched between the upper and lower cladding layers, that are called cover and substrate, respectively. The effective index n(x) is only a function of *x* coordinate. On the other hand, non-planar waveguides have optical confinement in two dimensions. Cladding surrounds the core in all transverse direction, and effective index n(x, y) is a function of both *x* and *y*. This geometry based classification of waveguides is shown in the flowchart in fig. (3.2) below.

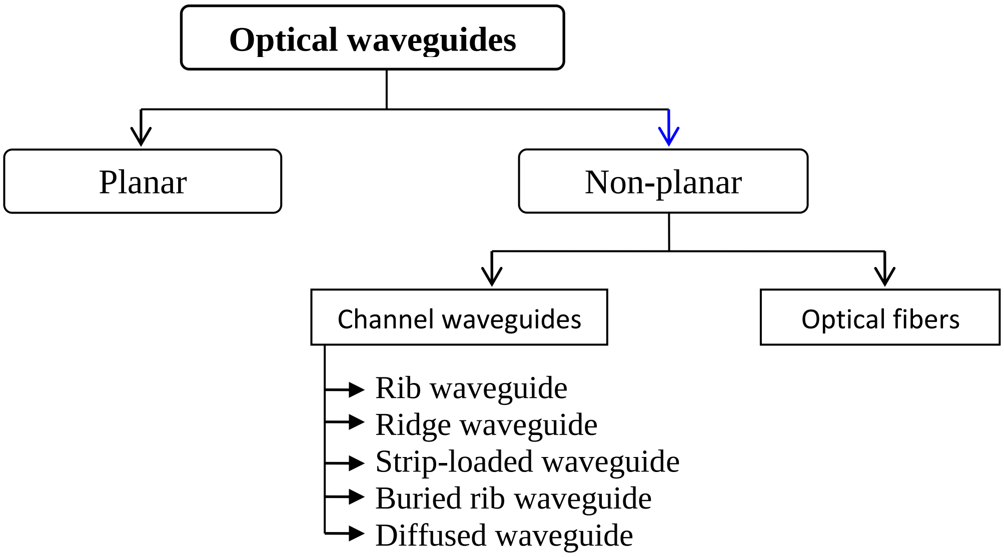


Fig 3.2: *Classification of optical waveguides based on their geometry*

Non-planar waveguides have a distinctive property that along with TE and TM modes, they also support hybrid modes. These hybrid modes are not supported by planar waveguides. Optical fibers are non-planar waveguides that have cylindrical structure. These types of waveguides exhibiting special geometrical structures can be analysed analytically. However channel waveguides are generally analysed numerically since there are no analytical solutions for their guided mode characteristics. The non-planar channel waveguides find various applications in photonic optics. Different channel waveguides are shown in fig. (3.3).

A **buried channel waveguide** has a high refractive index waveguiding core that is buried in a low-index cladding surrounding it. The core of the waveguide can have any cross-sectional geometry; however the rectangular shape is the most common. A **strip-loaded waveguide** consists of a planar waveguide that gives optical confinement to the light in one direction, which is loaded with a dielectric strip of index less than that of the core of the planar waveguide, or with a metal strip to provide optical confinement in the other direction. Strip waveguide has the waveguiding core region that is the region under the loading strip. A **ridge waveguide** structure is similar to that of the strip waveguide, but the high index region is actually the ridge or the strip that is on top of the planar structure. This high index acts as the waveguiding core. A ridge waveguide is surrounded by air on three sides which acts as the cladding material having low-index. It provides strong optical confinement. In **rib waveguide,** the strip is the part of the waveguiding core as it has the same index as the high index planar layer beneath it. Apart from this difference, the structure of the rib waveguide is similar to that of a strip or ridge waveguide. These four waveguides discussed above are also termed as rectangular waveguides though they do not have exactly rectangular shapes. A **diffused waveguide** involves creating a high-index region in the substrate itself by diffusing dopants in it. In this waveguide, the boundaries of the core are not sharply defined in the substrate.

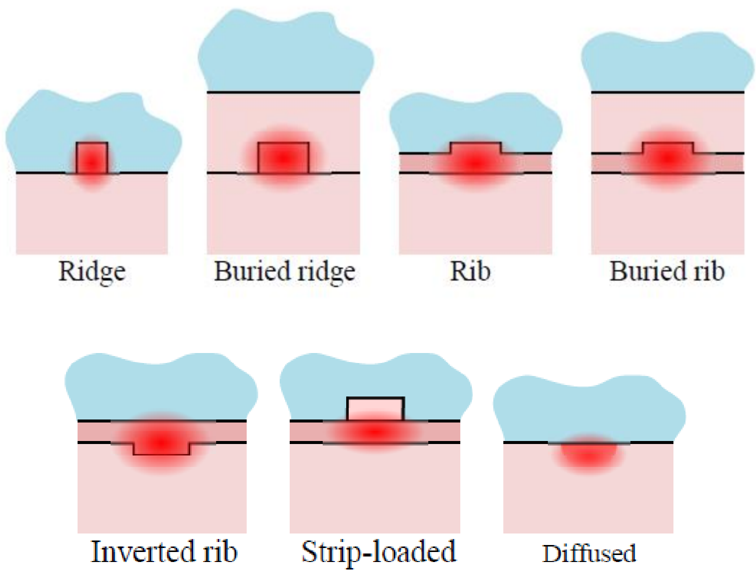


Fig 3.3: *Different types of channel waveguides based on total internal reflection (darker colour indicates higher index region). Taken from ref. [78]*

3.2.2. Guiding Mechanism and Propagating Modes of the Optical Waveguides

Waveguiding in optical waveguide generally involves three guiding mechanisms:

- Index guiding
- Low loss leaky wave guiding
- Gain guiding

The index guiding mechanism is the most common guiding mechanism which is based on total internal reflection (TIR). The channel waveguides like rib, ridge waveguide etc, follow this guiding mechanism. So they have a high refractive index core surrounded by lower refractive index cladding layers. This requires selection of suitable waveguide material and fabrication methods. The next guiding mechanism is basically based on guiding low loss leaky waves. This does not put restrictions on the selection of material for optical waveguides. Anti resonant Optical waveguides (ARROW) particularly use this guiding mechanism. The third guiding mechanism is gain guiding. It is used in semiconductor lasers, where a positive gain medium is created in the active region of laser diode due to the current flowing through it. This gain medium laterally guides the light, and thus called the gain guiding mechanism.

Waveguide mode is the light wave that is propagating inside the waveguide with a particular group velocity, electric-field distribution and polarization. Thus it has the electric and magnetic field components of the form $f(x, y)e^{i(\omega t-kz)}$, where z is the direction parallel to waveguide axis. These modes totally depend on the structure and characterize it in terms of electromagnetic resonances, and have no relation to the source of radiation of the waveguide. Thus these modes are called the ‘characteristic waves’ of the structures. Modes propagating inside the waveguide can also be defined as the superposition of plane waves that are travelling at a fixed angle with the axis of the waveguide.

According to the principle of total internal reflection, there are only a limited set of angles that are possible inside a waveguide, each of which corresponds to a propagating mode of the optical waveguide having a particular optical field distribution. Thus, depending upon the number of modes the waveguide can support at a particular wavelength, the waveguide can be said to be single-mode or multimode. Both types have their own applications and advantages. The single-mode waveguides exhibit low dispersion, thus they are usually preferred for telecommunication and sensing applications. Multimode waveguides find their application in illumination etc. The number of modes that are supported in a particular waveguide can be controlled by changing its dimensions. Smaller waveguides support less propagating modes. The rectangular waveguide basically show the following two types of mode, the transverse electric or the TE mode, and the transverse magnetic or the TM mode [79]. These are based on the polarization of the light propagating in the waveguide, TM mode has electric field component parallel to the substrate and TM mode has magnetic field component parallel to the substrate.

Channel waveguides are known to be one of the most important passive elements in integrated optics. They are the fundamental building blocks in all-optical photonic integrated circuits. When the channel waveguides are used in optical systems, we should ensure single mode propagation because they are further coupled with the single-mode fibers, which are used for communication. Soref, Schmidtchen, and Petermann1 reported the first single-mode condition for silicon rib waveguides using a mode matching technique. It was given as

$$t < \alpha + \frac{r}{(1-r^2)^{1/2}}; \quad \alpha = 0.3; \quad r \geq 0.5 \tag{3.5}$$

Where, t=W/H, r=h/H, h is the slab height, H is the rib height, and W is the rib width, as shown in Fig. (3.4). *Pogossian et. al.* later predicted the same condition as equation () but with α=0 using the effective index method of analysis. This result agreed more favourably with the experimental data [80].

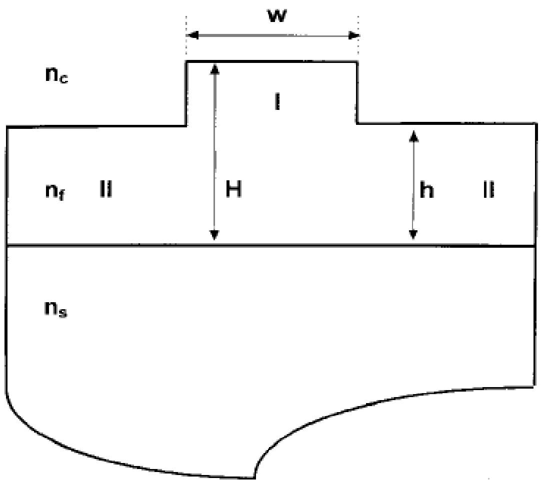


Fig 3.4: *Schematic of a rib waveguide structure. (taken from ref. [80])*

3.3. Modelling Methods for Waveguide Analysis

There are several techniques of solving the field problems, which we can classify as experimental, analytical and numerical. Experimental techniques are generally time consuming and expensive. They are also not flexible in terms of parameter variation. The analytical techniques provide exact solutions, but they involve difficult and lengthy calculations which require the knowledge of higher mathematics. Numerical techniques [81], on the other hand, let the operators carry out the actual work. They, however give the approximate solutions to the problem. Numerical techniques have applications in solving problems in fields like electromagnetics, fluid, acoustics and heat-transfer. These techniques are implemented using commercial software packages like COMSOL, RSoft etc. This section covers different numerical techniques that are used to solve the electromagnetic problems. Finding the numerical solution of a problem strategically has two approaches. The first approach deals with developing homemade numerical codes which has the advantage of flexibility in code modification due to full control over the code. The second approach involves the use of commercially available softwares like Computer Added Design (CAD). This approach is reliable, applicable to diverse physical problems and optimised in terms of memory, speed etc. Some of the numerical techniques are:

3.3.1 Finite difference method:

It is the technique that is based on replacing the differential equations by finite difference equations. It is a method of approximations, developed in 1920s by A.Thom. Initially it finds application in solving nonlinear hydrodynamic equations. This technique can now however be used to solve problems in different fields. The solution region is first divided into grid of nodes. Then the finite difference equivalent is approximated for a differential equation that relates the dependent variable located in the solution region to its neighbouring values. Then the suitable initial and boundary conditions are applied to solve the difference equations. The difference equations that are approximated are algebraic in form.

Finite difference time domain (FDTD) method is a time-domain numerical analysis method for solving scattering problems. In this the Maxwell's equations are solved using central-difference approximation to calculate the electromagnetic field in depressive media of different properties for the wide range of wavelength. It is a versatile and robust approach to solve for complex propagation constants. Few drawbacks of this method are memory complexity of algorithm and time consuming approach.

3.3.2 Variational method:

It is a numerical technique that gives accurate results with less usage of computer time and storage. In this technique, the complex problem of integrating the differential equation is replaced by equivalent variational problem. The other numerical techniques like finite element method and method of moment find a base in this method. The variational problems can be solved using two different methods. The first method is called the direct method which is a classical Rayleigh-Ritz method. The other method is called the method of weighted residuals or indirect method. The solution of a partial differential equation using the indirect variational method involves: first replacing the integral into variational form, then using the suitable method to find the approximate solution to the problem.

3.3.3 Method of moments:

The method of moments (MOM) is a general technique of solving an inhomogeneous equation of the form $L\phi=g$, where L can be integral, differential or intro-differential operator. Φ is the function to be solved and g is the excitation function. It is basically a method of weighted residuals. This numerical technique may be used to solve a variety of problems which include scattering problems, analysis of lossy structures and microstrip, radiation due to thin wire elements and other problems of practical interest. It involves finding the weighing function and then taking moments by multiplying with that function and then integrating. The procedure of solving problems using method of moments involves the following steps:

i. Using the weighing and basis function, conversion of the derived integral equation into a matrix equation.
ii. Evaluation of each matrix element.
iii. Finally, getting the parameter of interests by solving the matrix equation.

3.3.4 Finite element method:

Finite element method (FEM) is a versatile and more powerful numerical technique than previously discussed techniques, even though these techniques are easier to program and conceptually similar. FEM is an efficient method to solve problems that involve inhomogeneous media and complex geometries. This method can be applied to solve problems in various areas of physics like electromagnetics, waveguide problems, structural analysis, microstrips, semiconductor devices, etc. 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 subregions which are called finite elements. Analysing a problem using FEM technique involves few steps as described below:

i. Dividing the solution region into sub-domains or finite elements
ii. Solving a particular element to obtain governing equations.
iii. Assembling all sub elements to obtain the system of equations.
iv. Solving the system of equations.

CHAPTER 4

Chalcogenide Rib Waveguide Design for Slow Light Applications

4.1. Introduction

Realisation of slow light in optical fibers is known to have several applications and a lot of work is being done in this area as mentioned earlier. However on-chip realisation of SBS slow light is still very less explored. *Pant et. al.* reported for the first time the maximum delay of~23 ns for a 7 cm long chalcogenide rib waveguide [35]. It is difficult to observe slow light effect in an optical waveguide because to achieve a significant delay (ΔT_g) in a small length (L), we require a large group refractive index change (Δn_g) since $\Delta T_g = L\Delta n_g/c$. In this work, we have attempted to improve the time delay of the SBS based slow light and study other features of slow light in optical waveguides. We have designed an As_2Se_3 based chalcogenide glass rib waveguide for the generation of SBS based slow-light. The modal analysis of the proposed structure has been performed using commercially available software 'COMSOL Multiphysics' which is based on finite element method. We have solved two non-linear coupled SBS equations for the chalcogenide rib waveguide structure using the optical properties of As_2Se_3 based chalcogenide glass [82]. Effective-mode-area and confinement loss have been calculated using the imaginary part of the effective index of the propagating mode at the pump wavelength of 1.56 μm. Time delay of the propagating pulse and figure of merit has been calculated, thereafter, variation of the time delay with pump power and brillouin gain has been obtained by developing MATLAB codes.

4.2. Method of Analysis

We have used the finite element analysis method to simulate the waveguide model to calculate the guide loss and effective mode area. Finite mode analysis for the waveguide design is carried out using COMSOL Multiphysics 4.2. COMSOL is a simulation package that solves systems of coupled nonlinear partial differential equations in one, two and three dimensions. It is platform independent and has several add on module which can solve problems in different fields like electromagnetics, MEMS, chemical engineering, mechanics, etc.

The complex propagation constant of the fundamental mode is determined using a 2D full-vector eigenvalue solver. The fields localised in the core of the waveguide rather than distributing in the simulation boundaries, ensure that a true guiding mode is being propagated. For a guided mode to exist, in the absence of free charges and currents, the boundary conditions are as shown:

$E_{t1} = E_{t2}$ (Parallel Electric field is continuous across the boundary)

$\varepsilon_1 E_{n1} = \varepsilon_2 E_{n2}$ (Perpendicular component of εE is continuous across the boundary)

$B_{t1} = B_{t2}$ (Parallel Magnetic field is continuous across the boundary)

$B_{n1} = B_{n2}$ (Perpendicular Magnetic field is continuous across the boundary)

The mode field is solved using the wave equation that is given by:

$$\Delta(\varepsilon_r^{-1}\Delta \times H) - k_o^2 \mu_r H = 0 \tag{4.1}$$

The waveguide is discretized into smaller elements, then the electric and magnetic field across each element is solved for, separately. The boundary conditions mentioned above are applied between those elements with different properties. Then the propagation constants are solved for. The finite element method gives solutions for the electric mode with complex propagation constants β. Since some of the light entering in the core of the waveguide is propagating, while some is evanescent, the real part of the propagation constant gives the effective index, while the imaginary parts gives the loss.

$$n_{eff} = Re\left(\frac{\beta}{k}\right); \qquad loss = Im(2\beta) \tag{4.2}$$

Here, k=2π/λ is the wave vector, λ is the free space optical wavelength. Loss is incurred due to the constant flow of power from the core to the cladding or substrate. The guide design can be adjusted using this method to minimize the fundamental mode loss. [83,84]. The confinement loss is defined using the imaginary part of the effective index of the modes and it is given by

$$CL\left(\frac{dB}{m}\right) = \frac{40\pi}{\ln_{10}\lambda} Im(n_{eff}) = 8.686 k_o Im(n_{eff}) \tag{4.3}$$

4.3. Rib Waveguide Design

We have proposed an As_2Se_3 based chalcogenide rib waveguide for single mode operation for the generation of slow light based on stimulated brillouin scattering. The cross sectional view of the proposed rib waveguide is shown in Fig. 4.1. The substrate material used is silica (n=1.444). The core material used in the rib is As_2Se_3 based Chalcogenide glass. Chalcogenide has a refractive index of 2.815 for operating wavelength of 1.56 µm. The optical properties of As_2Se_3 based chalcogenide material are taken from the Ref. [82] and represented in the table 4.1.

Table 4.1. Optical properties of As_2Se_3 based chalcogenide glass at 1.56 µm.

Parameters	Chalcogenide (As_2Se_3)
Refractive index, n	2.815
Brillouin gain coefficient, g_B(m/W)	6.75×10^{-9}
Brillouin gain bandwidth, Δv_B (MHz)	13.2
Loss (dB/m)	0.90

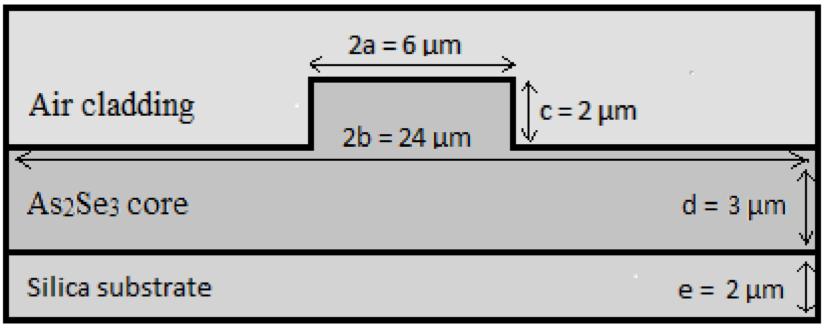


Fig 4.1: *Cross sectional view of As_2Se_3 based chalcogenide rib waveguide*

4.4. Result and Discussion

For optimum single mode operation with low loss we have taken the rib half width *i.e.*'*a*' as 3 µm and trench height as 2 µm. For these values, we have found the effective mode area of the waveguide to be 17.10 µm^2. The electric field distribution of the fundamental mode of the proposed structure is shown in Fig. 4.2 at pump wavelength. It can be observed that the mode is well confined within the rib. The effect of the variations in the width and the trench height of the waveguide on effective mode area are shown in Fig. 4.3. It is shown that effective mode area increases on increasing the width of the waveguide and also on increasing the trench height.

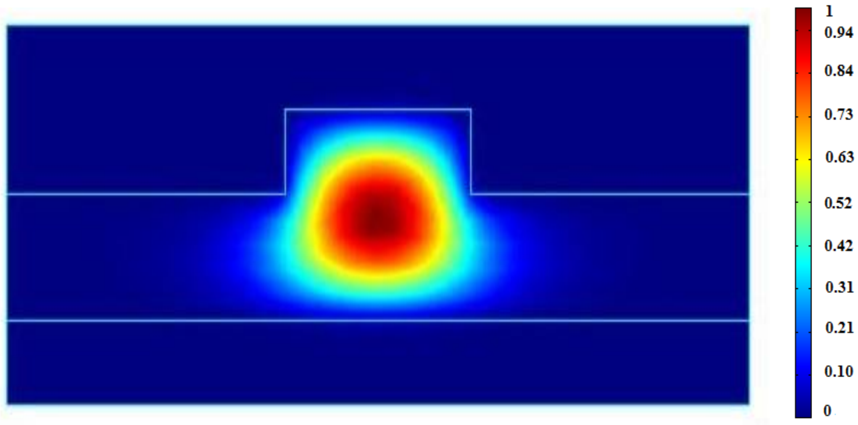
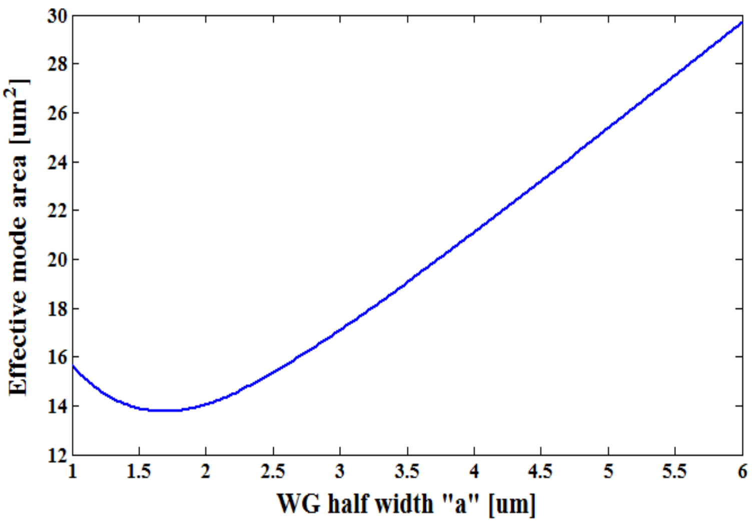
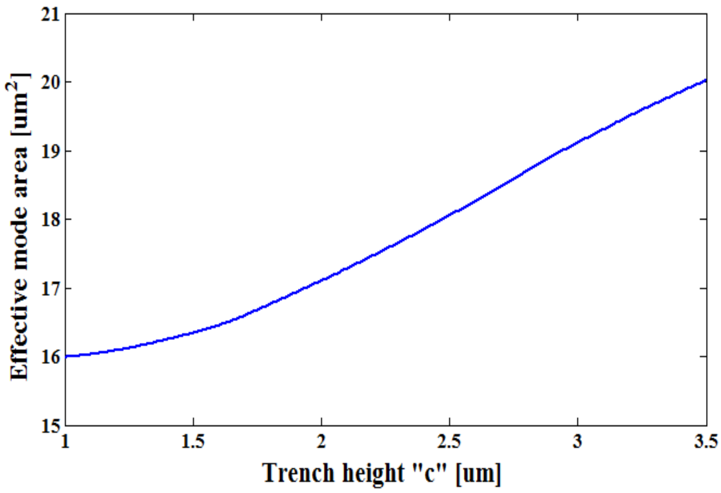


Fig 4.2: *Electric field distribution of fundamental mode in proposed rib waveguide at pump wavelength*



(a)



(b)

Fig 4.3: *(a) Variation of effective mode area with half width of waveguide*

(b) Variation of effective mode area with trench height

Confinement loss of the waveguide is another important parameter of the optical waveguide. The effect of changing the core width on confinement loss is shown in Fig. 4.4. It shows that the confinement loss decreases on increasing the core width. It so happens because as the core width increases, the core-cladding refractive index difference increases. This causes the electric field to be more confined in the core of the waveguide, thus higher confinement of light in core and lower confinement loss.

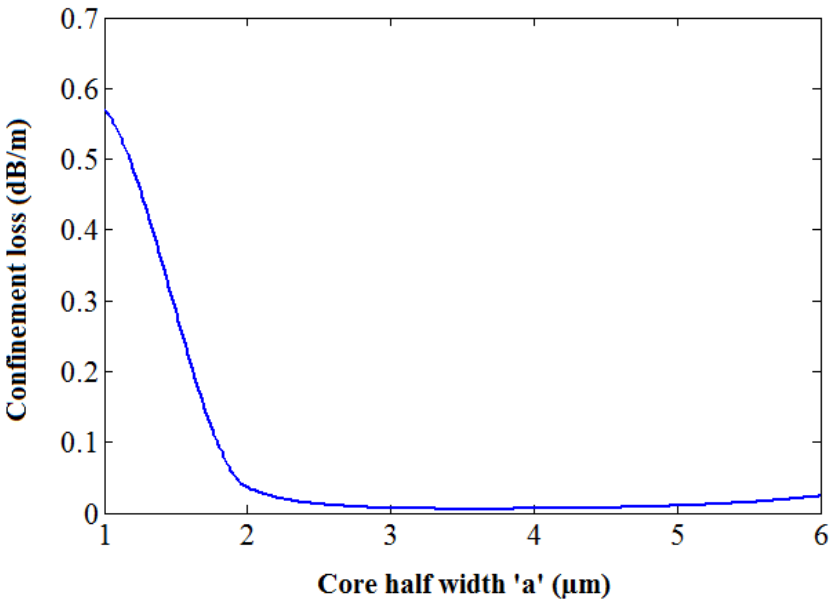
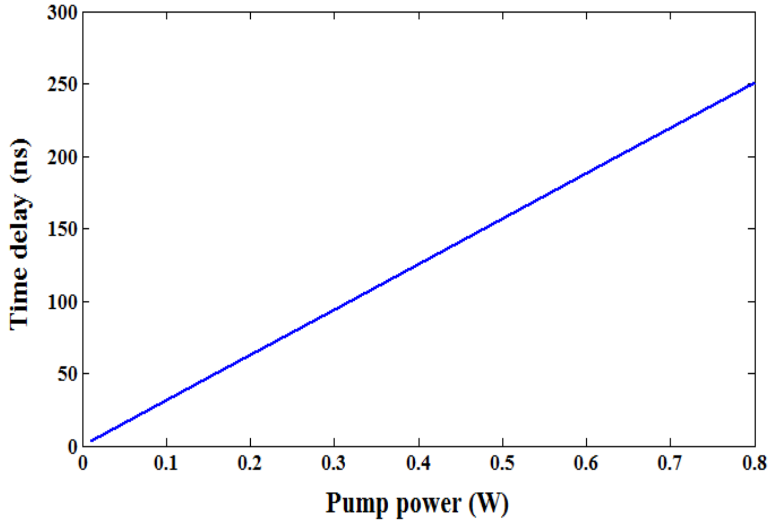
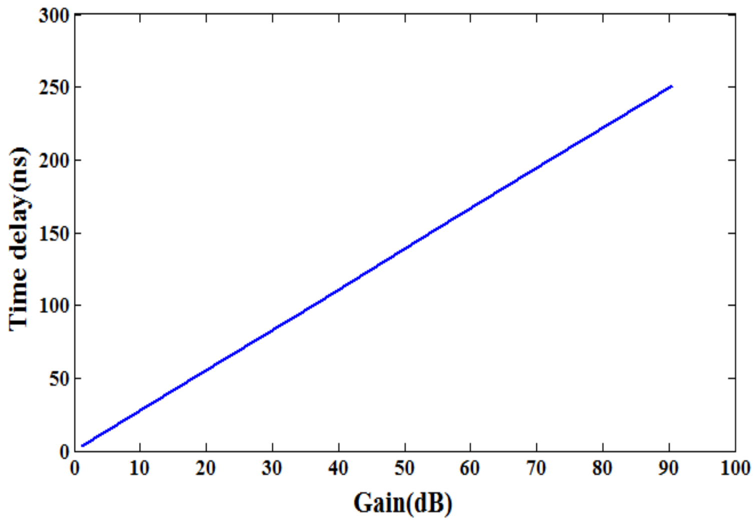


Fig 4.4: *Variation of confinement loss with core half width.*

From the previous results, the value of polarization factor K is taken to be 0.667 to find various parameters of slow light like minimum and maximum input pump power, time delay, Brillouin gain and figure of merit (FOM). For the operation at 1.56 µm wavelength, the minimum input pump power to initiate SBS effect and maximum input pump power for undistorted output is found to be 0.79 mW and 806 mW, respectively. Thus we have taken the pump power P_p as 800 mW in simulation. At this pump power, for a waveguide of 10 cm length, time delay is calculated to be ~251 ns. The effects of the variation of the pump power and the brillouin gain on the time delay of the waveguide are shown in Fig. 4.5. The figure of merit (FOM) of the proposed design is calculated and comes out to be 401.58.



(a)



(b)

Fig 4.5: (a) *Time delay as a function of pump power*

(b) *Time delay as a function of brillouin gain*

CHAPTER 5

Modified Ridge Waveguide Design for Generation of Slow Light

5.1. Introduction

In the previous chapter, we have analysed the As_2Se_3 based chalcogenide rib waveguide for slow light applications. Generation of slow light in that structure required quite large pump power. We have obtained the max power for undistorted output to be 809 mW. The pump power can be lowered by changing the design of the structure alone, to obtain more optimised parameters. In this chapter we have designed and analysed the modified waveguide design for generation of slow light with tunable features. The As_2Se_3 based chalcogenide glass ridge waveguide has been designed to obtain SBS based slow light effect. The pump wavelength is taken to be 1.56 µm. Effective mode area and confinement loss have been calculated. Then the time delay and its variation with the pump power and Brillouin gain have been obtained. Here we have also obtained the variation of time delay with the length of the waveguide.

5.2. Method of Analysis

The proposed waveguide is simulated and analysed using the simulation software COMSOL multiphysics 4.2 using finite element method. This method of analysis is similar to that used for chalcogenide rib waveguide design and is discussed in section 4.2 of chapter 4.

5.3. Ridge Waveguide Design

The cross-section of the modified ridge waveguide is shown in fig. 5.1. The material used for the ridge or the core of the waveguide is As_2Se_3 based chalcogenide glass having a refractive index of 2.815 at the pump wavelength. The substrate is made of silica. The optical properties of As_2Se_3 based chalcogenide are mentioned in Chapter 4 in table 4.1. The ridge width 'a' and height 'c' are the parameters that are varied to calculate the effective-mode-area 'A_{eff}' and confinement loss of the fundamental mode of the waveguide. Nonlinear parameter 'γ' is calculated and its variation with the half width of the core is observed. Further, the time-delay is observed and its variation with the pump power, gain and length of the waveguide are shown. The length of the waveguide is taken to be 10 cm.

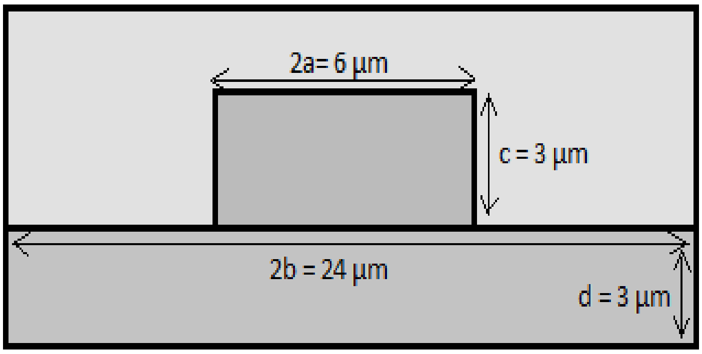


Fig 5.1: *Cross-sectional view of the As_2Se_3 based chalcogenide ridge waveguide structure.*

5.4. Numerical Result and Discussion

The design parameters shown in fig. 5.1 are the optimised parameters for single mode operation. The normalised electric field distribution of fundamental mode at ridge half width (*i.e.*'*a*') as 3 µm and trench height (*i.e.* '*c*') as 3 µm is shown in fig. 5.2.

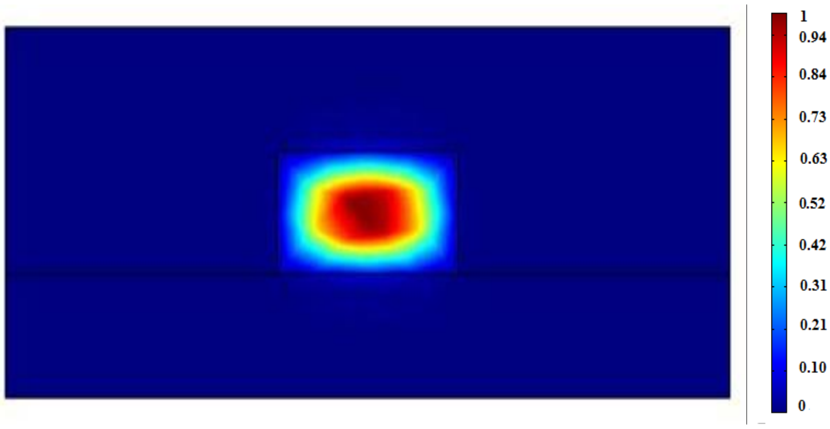
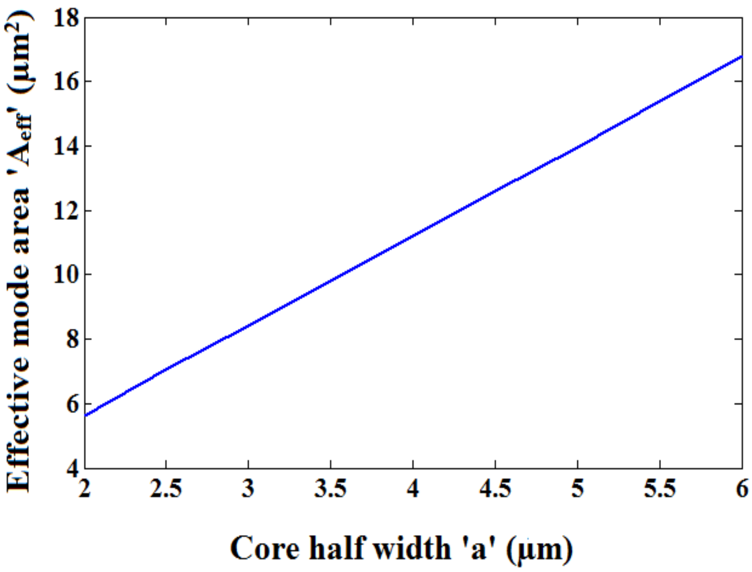


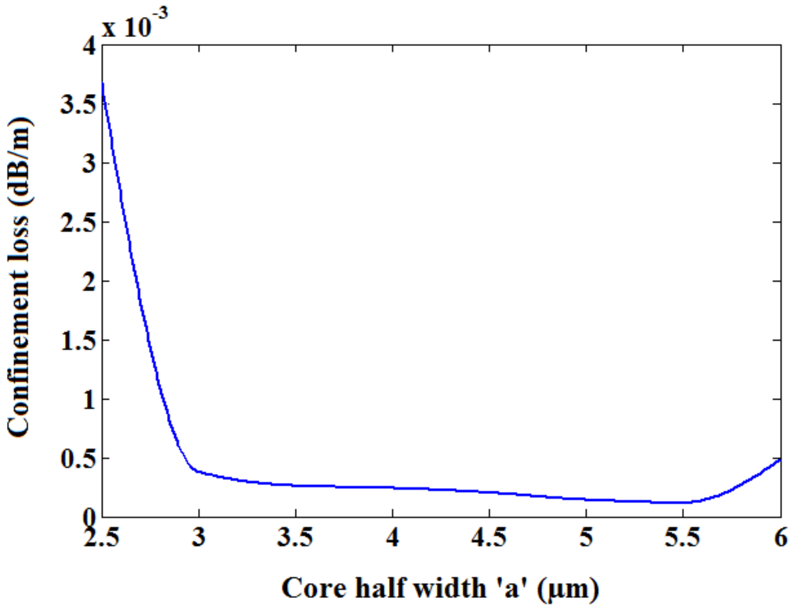
Fig 5.2: *Normalized electric field distribution of fundamental mode in proposed ridge waveguide at pump wavelength.*

The effective-mode-area of an optical waveguide enhances its nonlinear effect. Nonlinearity of the waveguide is inversely proportional to the effective-mode-area. Thus it is considered a very important parameter in the study of slow light in ridge waveguide. The effect of the variations in ridge width on effective-mode-area is shown in Fig. 5.3(a). It is shown that effective-mode-area increases on increasing the width of the waveguide since the core size increases. At a = 2 µm, the value of the A_{eff} is found to be 5.64 µm^2 and increases for higher values of core half width. Since for optimum single mode operation with low loss, we have taken core half width as 3 µm, at this core width, the effective mode area of the propagating mode is 8.42 µm^2.

Confinement loss and its variation with changing the design parameters of the waveguide is now observed. At core half width of 3 µm, the confinement loss of the propagating mode is found to be as low as 4×10^{-4} dB/m. It is a very desirable result as it ensures very low-loss operation of the waveguide at the optimized dimensions. The effect of changing the core width on confinement loss is shown in Fig. 5.3(b). It shows that the confinement loss decreases on increasing the core width, thus more confinement of light in the waveguide core.



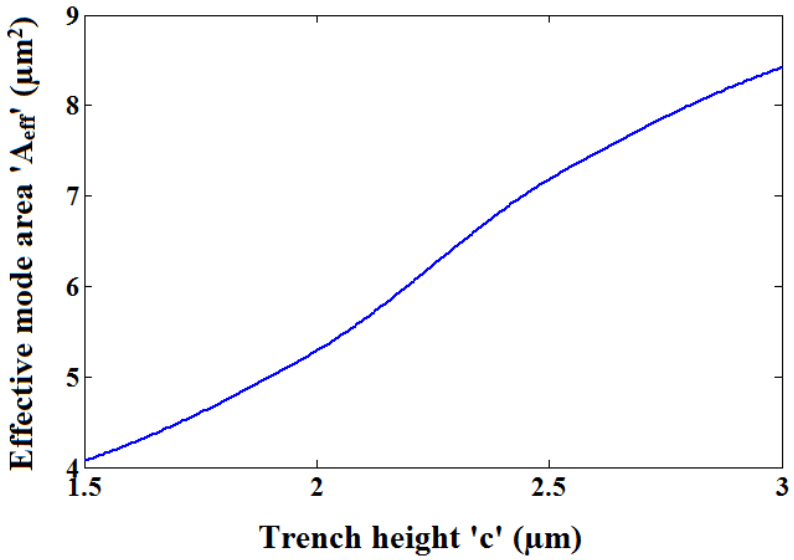
(a)



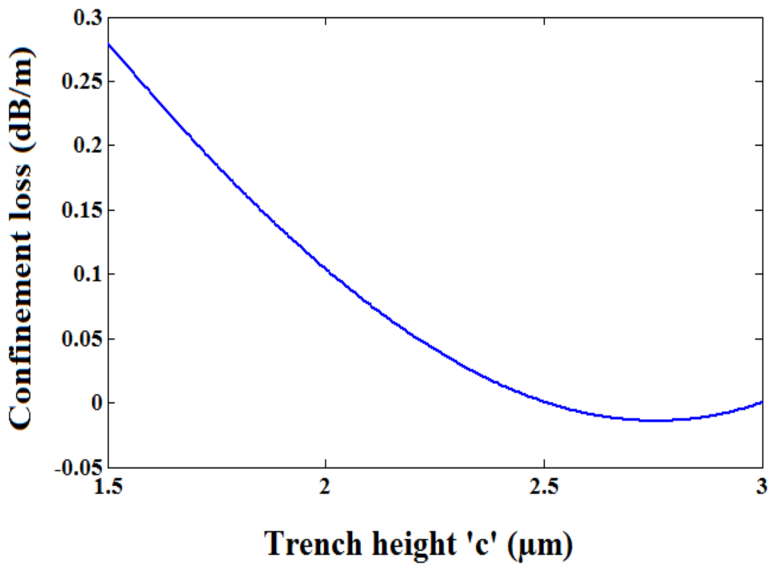
(b)

Fig 5.3: (a) *Variation of effective mode area with half width of the ridge waveguide.* ***(b)*** *Variation of the confinement loss with half width of the ridge waveguide.*

The effect of changing the trench height of the ridge waveguide on the effective-mode-area and confinement loss of the waveguide is also observed. The effective-mode-area increases on increasing the trench height '*c*' and the effect is shown in Fig. 5.4(a). As the height increases, effective refractive index difference also increases. Hence similar to the variation of confinement loss with '*a*', confinement loss also decreases with increase in height as shown in Fig. 5.4(b).



(a)



(b)

***Fig 5.4: (a)** Variation of the effective mode area with trench height of the ridge waveguide. **(b)** Variation of the confinement loss with trench height of the ridge waveguide.*

Nonlinearity of a ridge waveguide is another parameter that is taken into consideration while observing slow light in the medium. To get an enhanced SBS based slow light effect, it is necessary to have high non-linearity in the medium. For chalcogenide, this value is found to be 2.4×10^{-17} m^2/W when the input signal wavelength 'λ' is 1.56 μm []. For single mode operation at core half width of 3 μm, nonlinearity comes out to be 11.56 $m^{-1}W^{-1}$. Variation of nonlinear parameter with the core width is shown in fig. 5.5. It can be seen that nonlinearity decreases with increase in core half width.

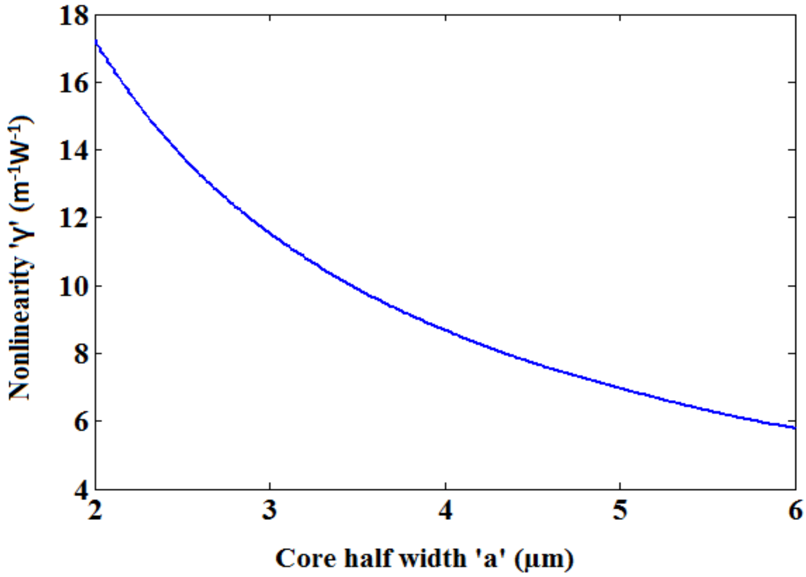
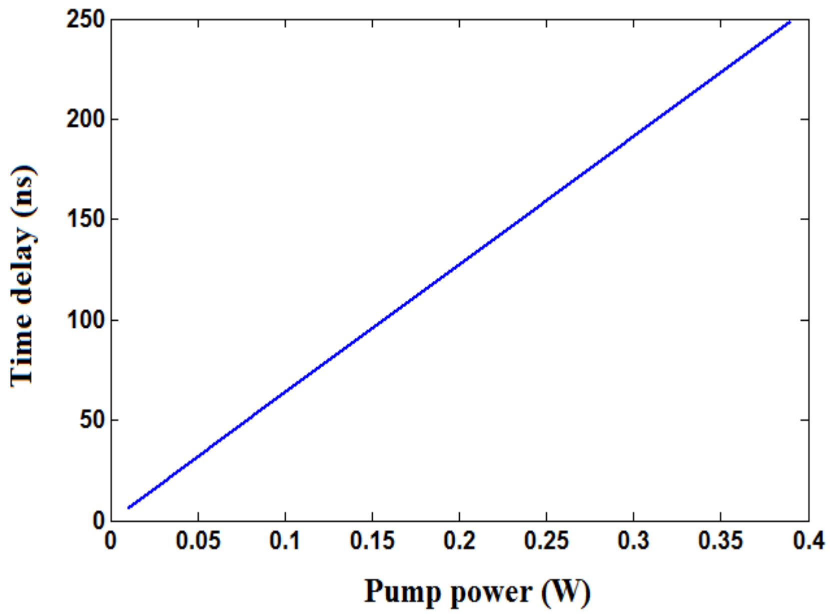


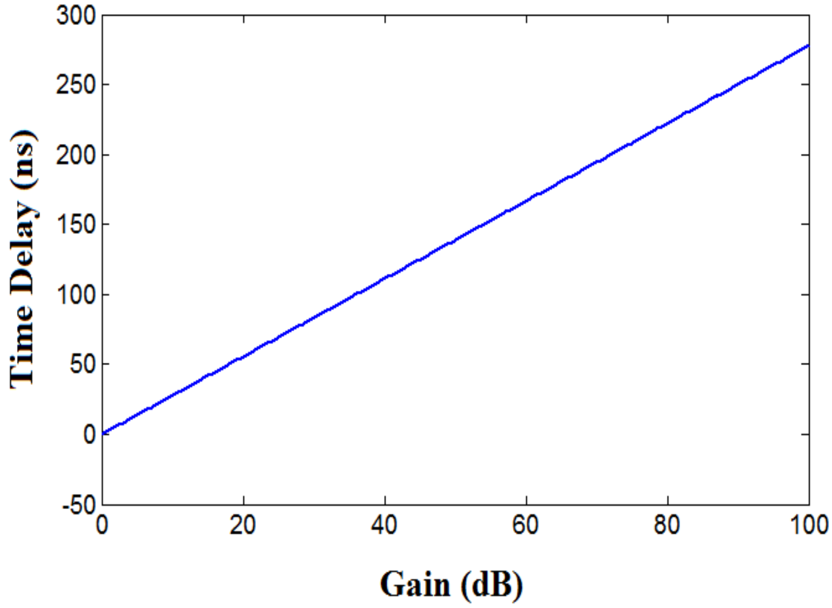
***Fig 5.5**: Variation of nonlinearity with half width of ridge waveguide*

The effective length of 10 cm long waveguide is calculated and it comes out to be 9.9 cm. Taking these values of L_{eff} and A_{eff} for single-mode operation and considering the optical properties of As_2Se_3, we have calculated maximum and minimum power. We get P_{max} = 396 mw and P_{min} = 0.3 mW. In our simulation, we have taken the pump power (P_p) as 390 mW to avoid distorted output for SBS based slow light operation. Here we observed that there is reduction in the max pump power requirement in this design. The value of polarization factor K is taken to be 0.667 as taken in the previous design.

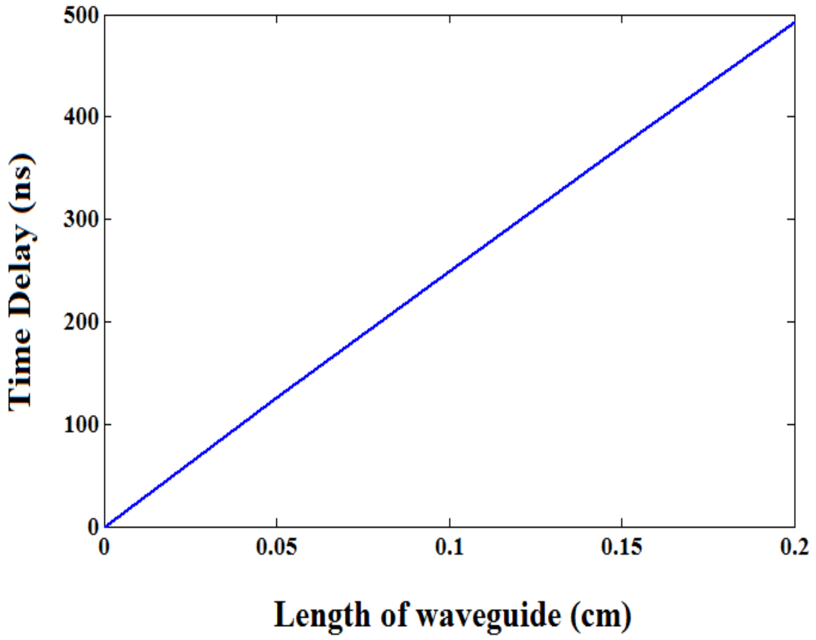
Finally, the time-delay in output pulse is calculated. We have achieved a maximum delay of ~249 ns for a waveguide of length 10 cm and input power of 390 mW. The time-delay is varied for different values of P_p ranging from 0.5 to 390 mW. The linearly increasing variation time delay with pump power is shown in Fig. 5.6(a). At higher input powers, the optical field substantially contribute to the phonon population. This simulated effect is the reason for linear increase of time-delay with pump power. Similarly, variation of the time-delay with Brillouin gain and with length of the waveguide is shown in Fig 5.6(b) and 5.6(c), respectively. The time-delay linearly increases with maximum delay reaching to 249 ns at 90 dB. The maximum time-delay of 493 ns is achieved for 20 cm long waveguide. Thus we can get the required time-delay by tuning the pump power, Brillouin gain and length of the waveguide.



(a)



(b)



(c)

Fig 5.6: *Time delay as a function of* ***(a)*** *pump power.* ***(b)*** *Brillouin gain.* ***(c)*** *length of the ridge waveguide.*

The theoretical gain (G_{th}) and figure of merit of the waveguide is also calculated to check the suitability of the waveguide for slow-light operation. We obtained the theoretical gain of 0.229 and FOM equal to 815.9 for the proposed structure.

CHAPTER 6

Conclusion and Future Scope

6.1. Conclusion

In this project, we have designed and analysed an As_2Se_3 based chalcogenide rib waveguide for tunable slow-light generation based on stimulated Brillouin scattering. To obtain the high nonlinearity, effective mode area of the rib waveguide has been controlled by varying the structural parameters of the waveguide. For the single mode operation, effective mode area of 17.10 μm^2 has been calculated. We have shown the variation of time delay with respect to input pump power and Brillouin gain. The maximum delay of ~251 ns has been calculated for 10 cm long waveguide at the input pump power of 800 mW. The stimulated results indicate that, in comparison to the previously reported work, much larger time delay has been achieved by changing the structural parameters and using higher nonlinear material.

Later we have proposed a modified ridge waveguide design to lower the input pump power requirements. For this waveguide design, we have obtained the effective-mode-area of 8.42 μm^2 and confinement loss as low as 4×10^{-4} dB/m for optimum single-mode operation. The max pump power required for SBS based slow light effect has been reduced to 390 mW. The time-delay up to ~249 ns has been achieved for this waveguide of length 10 cm. The variation of time delay with pump power, Brillouin gain and length of the proposed waveguide has been observed. . Finally we obtained a theoretical gain equal to 0.229 and FOM of the waveguide to be 816. The simulated results indicate that the slow-light can be obtained with tunable features by tuning the time-delay of the output pulse with pump power and other structural parameters of the waveguide. Thus it can be concluded that with high gain and FOM, the proposed ridge waveguide is suitable for SBS based slow-light applications with tunable features.

6.2. Future Scope

Stimulated Brillouin scattering based slow light effect has potential applications in compact slow light based photonic devices. A slow-light device is required to have a large and tunable slowdown factor, low loss, low power consumption, room temperature operation and compact device size. Focus needs to be done in improving each of these parameters. Increasing the non-linearity and delay of the slow light waveguide helps in realization of compact slow light devices. Integration of these structures with other photonic devices can eventually make the concepts of “slow-light engineering” and “chip-scale optical or quantum information processing” viable. Lots of improvement is needed in increasing the effective mode area of the fundamental mode for highly non-linear applications. Lowering of pump power requirement and enhancing nonlinearity can help in realization of all-optical devices using SBS based slow-light.

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