Taking Light For a Walk

Anita R Warrier and C Vijayan

Recent research on manipulating the speed of light has established the possibility of bringing down the speed of light to a value that can be challenged by a humble bullock cart. The processes that influence the speed of light in natural and artificial materials have been investigated in depth, leading to the design of specific techniques to slow down and even store light in appropriate medium at room temperature. We introduce here the basic science of slow-light propagation in materials and artificial structures such as photonic crystals and highlight the important milestones in research on this fascinating frontier.

(left) Anita R Warrier is a post-doctoral fellow at the Department of Physics, Indian Institute of Technology, Madras. Her research interests are in photothermal effect studies, semiconductors and photonic crystals.

(right) C Vijayan is a Professor at the Department of Physics, Indian Institute of Technology, Madras and is interested in the area of nanophotonics. For more information, see http://www.physics.iitm.ac.in/~cvijayan

1. The Enigma of the Speed of Light

> *"... yojananam sahasre dve dve shate dve ca yojane ekena nimisardhena kramamana namostu te ..."*

"Salutations to you, who traverse 2,202 *yojanas* in half a *nimesha"*: Sayanacharaya in *Rigvedabhashya.* [The equivalent value of this speed is close to 3×10^8 m/s, according to S C Kak, *Indian Journal of History of Science*, Vol.33, pp.31–36, 1998.]

The speed of light in vacuum has perhaps been the most intriguing fundamental constant in physics that has inspired the imagination of man to the greatest extent. Realization of its invariance across reference frames has revolutionized physics over the past century. Any idea of speeding up light (or anything else, for that matter!) beyond 3×10^8 m/s (denoted by c) has met with scepticism and awe. Much similar is the case with any talk of

Keywords
Slow light, EIT, photonic band gap.

Light has been demonstrated to travel at speeds much slower than c in certain natural and artificially designed structures and physicists are busy in recent years figuring out the details of this behaviour.

slowing down light. However, *slow light* is not all new to physics; work on reduction of speed of light below c began as early as 1800 when Hamilton showed that group velocity can be different from c.

Light indeed travels slower in material media than in vacuum. The nature of the complicated electronic processes of light–matter interaction in any given material eventually determines the speed of light in that material, which is characterized macroscopically by specifying its refractive index. The term 'slow light' is used with a slightly different connotation in recent literature, as we shall examine here. Light has been demonstrated to travel at speeds much slower than c in certain natural and artificially designed structures and physicists are busy in recent years figuring out the details of this behaviour.

There is an interesting reason for the *gold rush* to achieve *slow light*, apart from the obvious conceptual challenge: its promise in the design of optoelectronic devices with enhanced efficiency. The increased interaction time of slow light in a medium leads to a reduction in the required physical size as well as in its time of response. Due to enhanced light–matter interaction, slow light can be used to replace high power lasers to induce non-linear responses. The use of this technology can further improve the efficiency of nonlinear process by a factor of more than 10000. This increase in efficiency along with a possible reduction in size of devices can revolutionize the present design of optical switches, diodes and modulators, paving the way for the realization of the long-cherished dream of all optical, photonic and quantum computing devices.

2. Waves of Different Feathers Flock Together

The speed of light as it travels in vacuum is not the same as when it propagates through a medium. Also, greater the refractive index of the medium, slower is the

propagation speed. To understand what happens to a monochromatic light wave as it travels through vacuum, let us consider the propagation of a monochromatic electromagnetic wave in vacuum to be represented by the wave function $\psi(x.t)$ of the form,

$$\psi(x,t) = A\cos(kx - \omega t)\,, \qquad (1)$$

where ω is the angular frequency $2\pi\nu$, k is the magnitude of the wave vector (numerically equal to $2\pi/\lambda$ where λ is the wavelength) and A is the amplitude of the wave. For simplicity and ease of understanding the concepts, we may consider light to be propagating along the positive direction of the x-axis and ignore the vector nature of k.

The speed c of the wave propagating through vacuum is represented by ω/k, usually termed as the phase velocity of the wave, taken to be monochromatic. As the wave enters a medium of refractive index $n > 1$, the time-varying electric vector interacts with the permanent or induced electric dipoles in the medium, which oscillate and emit electromagnetic waves of the same frequency as the incident wave. The emerging wave experiences a drag due to interference of emitted waves with the incident waves. This is the classical way of understanding the propagation of light through matter.

If the incident light is in the form of a wave packet comprising of several individual monochromatic waves of different frequencies, the drag experienced by each monochromatic component is different and each wave propagates with a different speed, as described by the frequency-dependence of the refractive index $n(\omega)$. The group of waves propagating through a dispersive medium of refractive index $n(\omega)$ is represented by a combination of plane waves with different frequencies. For example, a combination of two such waves with the same amplitude

and slightly different frequency is given by,

$$\psi(x,t) = A\cos(kx - \omega t) + A\cos[(k+\delta k)x - (\omega + \delta\omega)t] \tag{2}$$

$$= 2A\cos\left[\left(k + \frac{\delta k}{2}\right)x - \left(\omega + \frac{\delta\omega}{2}\right)t\right]\cos\left(\frac{\delta k}{2}x - \frac{\delta\omega}{2}t\right). \tag{3}$$

Equation (3) represents the superposition of two waves in which each individual wave travels with its own *phase velocity* and an envelope of the combination is considered to be propagating with the *group velocity*. The first part of (3) represents the propagation of individual waves while the second part represents the propagation of the envelope. This treatment can be extended to describe a group consisting of a large number of monochromatic waves with different frequencies travelling together in a medium.

The magnitude of the *phase velocity* of any individual wave is equal to the speed of that wave in vacuum and is given by $v_{\mathrm{p}} = \omega/k$ and the *group velocity* of the envelope of the group of waves is given by $v_{\mathrm{g}} = \delta\omega/\delta k$ (*Figure* 1). The shape and location of the envelope (termed as the wave packet) are determined by the constructive and destructive interference of the waves constituting it.

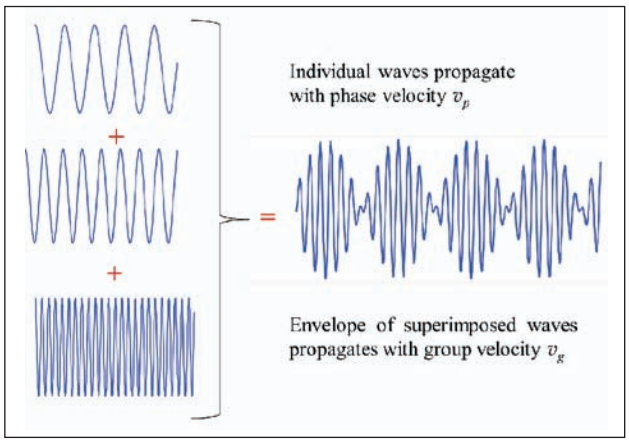

Figure 1. The envelope of a wave packet propagates with a group velocity v_{p} which may be different from the individual phase velocity v_{g} of any component wave. This schematic diagram shows a wave packet formed by the superimposition of monochromatic waves of three different frequencies.

This concept of group velocity was introduced by Hamilton in 1839 in his presentation at the Irish Academy and these ideas were accepted widely after the publication of the work of Stokes and Rayleigh several years afterwards.

3. 'Let there be color' and there was *dispersion*

For a wave packet made up of a group of waves travelling together with a speed v_g, the dependence of the refractive index on the frequencies of the individual monochromatic component waves of a wave packet leads to *dispersion.*

Consider the propagation of a wave packet of light through a medium with complex refractive index, $n(\omega) = n_r(\omega) + in_i(\omega)$, where n_r and n_i represent the real and imaginary parts of $n(\omega)$. The dependence of the refractive index on the frequency of the individual monochromatic component waves of a wave packet leads to dispersion. This wave packet is made up of a group of waves travelling together with a speed v_g. Dispersion in a medium is described in terms of a frequency-dependent wave vector whose magnitude is given by

$$k(\omega) = \frac{\omega}{c} n_r(\omega)\,. \tag{4}$$

The time taken (transit time) for the peak pulse to propagate distance z through the dispersive medium is

$$t_{\text{medium}}(\omega) = \frac{\mathrm{d}k}{\mathrm{d}\omega} z = \frac{z}{v_g(\omega)}\,. \tag{5}$$

The transit time for the wave to propagate through any medium would be different from that through vacuum, which is $t_{\text{vacuum}} = z/c$.

The relation of the dispersive nature of the medium to the optical absorption can be understood using the Kramers–Kronig relations (see *Box* 1) [1]. A medium is said to be dispersive for a certain type of wave if the

For a wave packet made up of a group of waves travelling together with a speed v_g, the dependence of the refractive index on the frequencies of the individual monochromatic component waves of a wave packet leads to dispersion.

Box 1. Revealing the Colors of Darkness

The dielectric constant of a dispersive dielectric medium governs the nature and extent of the response of the medium to an incident electromagnetic wave such as a light wave. It turns out that this is a complex quantity $\varepsilon(\omega) = \varepsilon'(\omega) + i\varepsilon''(\omega)$, with its real part ε' representing dispersion of light in the medium and its imaginary part ε'' representing absorption by the medium. *Figure* 1A shows the general nature of variation of the absorption coefficient and refractive index of a typical medium as functions of frequency ω of the incident electromagnetic wave.

Materials absorb light and other forms of electromagnetic radiation at specific frequencies determined by their electronic, vibrational or rotational energy level structure. The displacement vector $\vec{D}(t)$ is related to the electric field $\vec{E}(t)$ by the simple relation $\vec{D}(t) = \varepsilon\vec{E}(t)$ at lower frequencies, according to which, the value of the vector $\vec{D}(t)$ at a given instant of time t is determined completely by the value of the vector $\vec{E}(t)$ at that very instant. However, at higher frequencies, when the frequency of radiation is comparable to atomic frequencies, the polarization cannot keep up with the fast changes in the time-varying electric field producing it and becomes dependent on the values of $\vec{E}$ at earlier instants of time and hence the history of the process. Thus $\vec{D}(t)$ depends on the value of $\vec{E}$ at every previous instant – we may write the relationship between their magnitudes as

$$D(t) = \int_{\infty}^{t} \varepsilon(t,t')E(t')\mathrm{d}t' = \int_{\infty}^{t} \varepsilon(t-t')E(t')\mathrm{d}t' \,.$$

The corresponding Fourier transform of the equation can be written as,

$$D(\omega) = \varepsilon(\omega)E(\omega)\,,$$

where

$$\varepsilon(\omega) = \int_{-\infty}^{\infty} \varepsilon(t)e^{i\omega t}\mathrm{d}t\,.$$

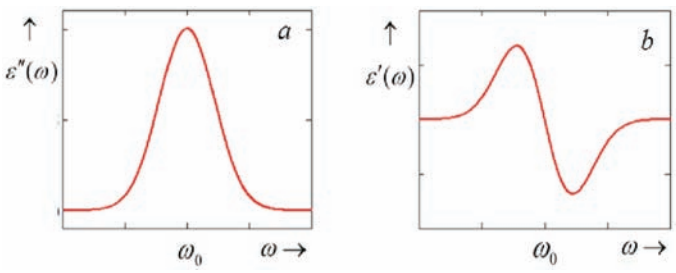

Figure 1A. Schematic plots (**a**) and (**b**) depict the general nature of variation of the imaginary part $\boldsymbol{\varepsilon''}$ and the real part $\boldsymbol{\varepsilon'}$ of the dielectric constant respectively, each as a function of the frequency ω of the incident electromagnetic wave in the vicinity of a resonance frequency ω_0 of the system. The quantities are given in arbitrary units.

Box 1 continued...

Box 1 continued...

If $\vec{E}(t \leq 0) = 0$ for all values of time t preceding $t = 0$, causality relations imply that $\vec{D}(t \leq 0) = 0$. This means that all the Fourier components of $\vec{D}(t \leq 0)$ interfere destructively for $t \leq 0$.

The existence of causal relation implying that $\vec{D}(t)$ at any time t is determined by polarization $\vec{P}$ (defined as dipole moment per unit volume) which occurred at all preceding times leads to an interesting consequence – the real and imaginary parts of the dielectric constant are related to each other [1]. Assuming that all functions describing the physical process can be extended in a Fourier integral, this relationship can be expressed as

$$\varepsilon'(\omega) - 1 = \frac{1}{\pi} P \int_{-\infty}^{\infty} \frac{\varepsilon''(x)}{(x-\omega)} \mathrm{d}x.$$

and

$$\varepsilon''(\omega) = -\frac{1}{\pi} P \int_{-\infty}^{\infty} \frac{\varepsilon'(x) - 1}{(x-\omega)} \mathrm{d}x.$$

These equations are called the Kramers–Kronig dispersion relations – they relate the real part of the susceptibility (which corresponds to dispersion) with the imaginary part (which corresponds to absorption). Thus Kramers–Kronig relations establish the connection between the two physical processes in the medium and imply that any change in absorption will be accompanied by a corresponding change in the refractive index at frequencies close to that of absorption.

velocity depends on the frequency. Dispersion is described as *normal* if the variation of refractive index with frequency is greater than zero, i.e., $(\mathrm{d}n/\mathrm{d}\omega) > 0$ and it is generally *normal* at values of ω far away from the resonance frequencies at which the material absorbs light. However, the refractive index becomes complex near the resonance frequency and possesses a large imaginary part, implying that the propagation of the wave is accompanied by absorption in the medium at frequencies close to resonance. For a dielectric medium the real part ε' of the dielectric constant ε is related to the refractive index by the relation $n = \sqrt{\varepsilon'}$, and decreases with increase in frequency around the resonance frequency. The medium thus possesses *anomalous dispersion* for frequencies in this range, where the absorption is also

Depending on the dispersive nature of the medium through which the beam propagates, the speed of light can be varied as it propagates and can in principle be made greater than c (fast light), less than c (slow light), zero (frozen light) or even negative (backward light).

the greatest. The shorter wavelengths are refracted to a smaller extent than the longer wavelengths near resonance.

Depending on the dispersive nature of the medium through which the beam propagates, the speed of light can be varied as it propagates and can in principle be made greater than c (fast light), less than c (slow light), zero (frozen light) or even negative (backward light). The dispersion in a medium is described by the group index

$$n_{\mathrm{g}} = n_{\mathrm{r}} + \omega \frac{\mathrm{d}n_{\mathrm{r}}}{\mathrm{d}\omega}\,. \tag{6}$$

The group velocity may be expressed in terms of group index as

$$v_{\mathrm{g}}(\omega) = \frac{\Delta\omega}{\Delta k} \cong \frac{\mathrm{d}\omega}{\mathrm{d}k} = \frac{c}{n_{\mathrm{r}} + \omega \frac{\mathrm{d}n_{\mathrm{r}}}{\mathrm{d}\omega}}\,. \tag{7}$$

Thus the term $\mathrm{d}n_{\mathrm{r}}/\mathrm{d}\omega$ of the medium plays a crucial role in determining the group velocity of a wave propagating through it. Depending on the value of the group index, the speed of light through a medium can be tuned to either fast or slow as it propagates through a medium. When $\mathrm{d}n_{\mathrm{r}}/\mathrm{d}\omega$ is large and positive, the speed is much reduced from c and we get *slow light*.

4. How to Win the Race to be Slow and Steady

The speed of light is reduced as it propagates through any material medium.

The speed of light is reduced as it propagates through any material medium. The velocity of a light beam propagating through a medium such as glass (of refractive index 1.5) is $0.67c$ and is further reduced to $0.41c$ while propagating through a medium of higher refractive index like diamond (of refractive index 2.4). However, these speeds are still considered too 'fast' for the light to be described as *slow light*. To achieve extreme slow light that the human eye can perceive, n_{g} is required to be of order of 10^8. Such slow light can be achieved in practice by experimental techniques such as electromagnetically

induced Transparency [EIT], stimulated Brillouin Scattering [SBS] and Stimulated Raman Scattering [SRS] or by engineering 'metamaterials', which are materials with specific structures designed artificially.

'Slow-wave structures' were used to slow down the speed of electromagnetic signals in microwave travelling tubes even as early as the 1950s. The axial velocity of the signal was reduced to electron beam velocity by choosing different forms of structural geometry of slow-wave structures. The prospect of slowing down light was investigated thoroughly in the past decade or so with special emphasis on identifying various possible methodologies for attaining slow light. McCall and Hahn observed slow light when they studied the effect of self-induced transparency in a ruby rod cooled by liquid helium, on excitation with a Q-switched ruby laser [2]. The transmission in nonlinear regime was explained as due to a partial saturation of the absorption by the leading edge of the pulse. Later, with the discovery of electromagnetically induced transparency (EIT, see *Box* 2), the group

Box 2. Making a Laser Beam Pass Through Opaque Media

Electromagnetically Induced Transparency (EIT) is a phenomenon in which an opaque medium is made transparent to a weak probe beam by making the material interact with a strong pump beam. This is achieved using an intense pump beam from a laser to manipulate the quantum states in an opaque cloud of atoms and making it transparent to a narrow range of wavelengths of light. There are several schemes of achieving EIT involving quantum mechanical processes such as coherent population oscillations between levels and spectral hole burning, details of which are beyond the scope of this article[1,2]. Some elementary idea on how this works can be had from *Figure* 2A.

Consider a three-level system being probed by a resonant probe beam with its wavelength corresponding to the energy difference between transitions involving two of these levels. Light from the probe beam is absorbed at this wavelength and an optical transmission spectrum would show a dip in a wavelength region close to the resonant frequency. Now consider the case when the system is made to interact with a high intensity laser beam which

[1] J B Khugrin, Slowlight in various media: a tutorial, *Adv. Opt. Photon.*, Vol.2, p.287, 2011.

[2] T Baba, Slowlight in photonic crystal, *Nature Photonics*, Vol.2, p.465, 2008.

Box 2 continued...

Box 2 continued...

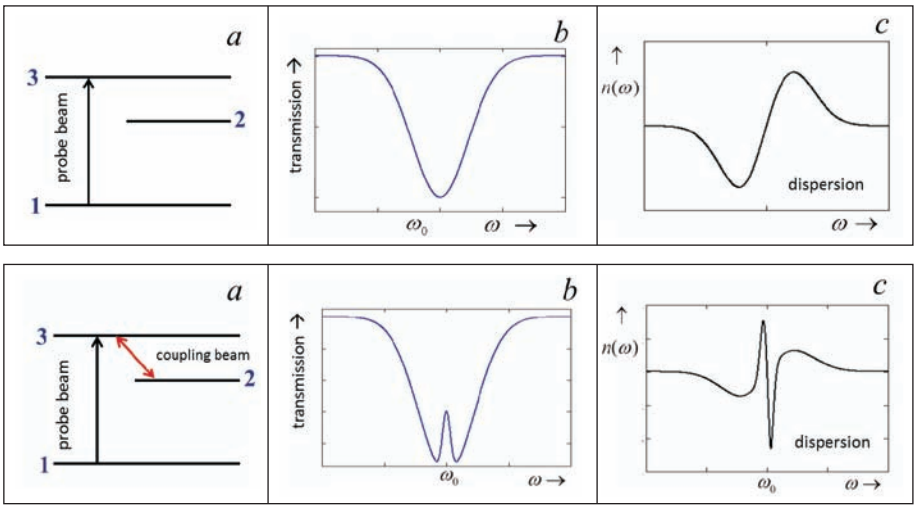

Figure 2A. One of the methods of achieving electromagnetically induced transparency (EIT). The system of energy levels shown in (**a**) can lead to a transmission spectrum depicted in (**b**) and the corresponding variation of the refractive index with frequency depicted in (**c**). The top panel refers to the situation without a coupling beam and the bottom panel shows the effect of an appropriate coupling beam. The plots are schematics with quantities in arbitrary units.

could cause modifications in the populations in these levels. Under appropriate conditions, this modulation of populations can lead to a decrease in optical absorption within the spectral band of absorption, resulting in the type of spectral features shown in the figure. Technically, this involves adjusting the magnitude of coupling fields associated with the three-level system leading to destructive interference between the probability amplitudes associated with the excitation pathways ($1 \rightarrow 3$, the direct pathway and $1 \rightarrow 3 \rightarrow 2 \rightarrow 3$, the indirect pathway). As a result of this, most of the population is optically pumped (through spontaneous emission from the level 3) to a dark state, which is a noncoherent superposition between levels 1 and 2. This amounts to a trapping of the population in the dark state which makes the medium transparent to the probe absorption[3].

This kind of an absorption spectrum leads to a very strong wavelength-dependence of the refractive index of the medium in a rather narrow spectral region, as described by the Kramer–Kronig relations (see *Box* 1). This leads to a corresponding variation in $dn_r/d\omega$ with a magnitude sufficient to slow down light. However, EIT has been demonstrated only in a few systems such as atomic vapors. Thus the prospect of any laser beam rushing towards you through the walls of your classroom need not bother you yet.

[3] J P Marangos, Topical review electromagnetically induced transparency, *Journal of Modern Optics*, Vol.45, No.3, p.471, 1998.

led by Stephen Harris at Stanford solved the problem of increased absorption at high dispersion thus demonstrating the practical feasibility of achieving slow light [3]. In 1999 Hau *et al* were able to bring down the speed of light to 17 m/s using EIT in an ultra-cold gas of Na atoms at 435 nK [4]. These results however did not receive adequate attention due to practical difficulties involved, such as the need to work at ultra-low temperatures and the fact that the achieved bandwidth of slow light was very narrow. A vast amount of research was pursued with focus on slowing light down considerably even at room temperature. These efforts succeeded when slow light was achieved in a solid material at room temperature using *coherent population oscillation.* In 2006, Schweinsberg *et al* and Gehring *et al* demonstrated slow-light propagation in an erbium-doped optical fiber at room temperature [5, 6].

Two other mechanisms to slow light at room temperature are stimulated Brillouin scattering and Raman scattering where slowing is achieved by inducing a high frequency acoustic wave and vibrational excitation in the material. In this technique, energy is transferred from a high frequency beam to the low frequency beam and the frequency difference equals the characteristic acoustic frequency of the material. This gives rise to a spectrally varying refractive index which can be tuned by changing the power of the pump beam. This technique was used to delay an optical pulse in an optical fiber where scattering occurs due to highly localized changes in the dielectric constant of the medium. An important advantage of this technique is that light is slowed at a wavelength that is offset from the pump beam by a material-dependent frequency and this is a useful feature in telecommunications.

The use of slow light in optical delay lines, buffers and non-linear optical devices can solve several problems that block further advancement in photonics technology. To

The use of slow light in optical delay lines, buffers and non-linear optical devices can solve several problems that block further advancement in photonics technology.

Scientists are working on building slow-light systems that can be easily incorporated in *chips* and *wafers*. This would be feasible only if slow light can be obtained using techniques operating at room temperature.

bring out the full potential of slow light in this field, scientists are working on building slow-light systems that can be easily incorporated in *chips* and *wafers*. This would be feasible only if slow light can be obtained using techniques operating at room temperature. It should also be possible to integrate it into materials that can be easily engineered to suit the *size zero* demand of technology. Recent work on dielectric metamaterials seems to offer relief to some of the prevailing technical woes by enabling the design of dielectric materials to form *photonic band-gap structures* which can be made to function as slow-light structures and can be incorporated rather easily into chips by means of lithography at room temperature.

5. Falling Flat on Going Through *High* and *Low*

Recent research on metamaterials has enabled the design of *photonic band-gap structures* which can slow down the propagation velocity of visible light under appropriate conditions. Photonic band-gap structures are artificial structures constructed with very thin alternate layers of dielectric material with high and low values of refractive index and appropriate thickness (see *Box* 3). For example, this can be achieved by structuring a periodic array of high refractive index material with regularly placed air holes within. Photonic band-gap structures can be fabricated by layer-by-layer deposition, self-assembly, etching by lithographic or holographic techniques. Such 1-D, 2-D and 3-D periodic arrangements have been reported in Si wafer, SiO_2, GaAs, InP, CdS, etc. [7]. The periodic geometry of these structures makes it convenient to control and manipulate the flow of light. Slow-light generation due to structural dispersion has a greater significance compared to other slow-light mechanisms which require sophisticated instrumentation that deter the utility of this phenomenon. Slow light can be achieved in photonic crystals with different values of group velocity by adjusting the refractive

Recent research on metamaterials has enabled the design of *photonic band gap structures* which can slow down the propagation velocity of visible light under appropriate conditions.

Box 3. Beauty is Many-a-Layer Deep!

Dispersion of light arising from structural features at micro and nano levels is the mechanism Nature adopts to provide brilliant hues to butterfly wings and peacock feathers. The details of the actual physical origin of color and its relationship with structural features was not understood till quite recently, until man started designing artificial periodic structures called metamaterials and observing several interesting optical properties in these materials. The periodic geometry of these structures with variation in refractive index renders them as Bragg reflectors which reflect wavelengths of same order as the periodicity of these structures. Man-made structures called photonic crystals act similarly, to reflect a particular band of light (when refractive index contrast between the layers is sufficiently high) to form photonic band gaps (*Figure* 3A).

The formation of such gaps, which completely reflect a band of wavelengths, is analogous to the formation of band gaps in crystalline semiconductors where the electrons are forbidden to take a certain band of energy values. The band gap in a semiconductor arises as a consequence of an electron wave experiencing a periodic potential in a crystal. Similarly, the photonic band gap is a consequence of a light wave encountering alternating values of refractive index in an appropriately layered dielectric material. Thus we may say that a photonic crystal does to a light wave what a crystalline semiconductor can do to an electron wave. These structures also give rise to several exotic phenomena such as enhanced Raman scattering, increased stimulated emission, super prism behaviour and negative refraction[1].

The plot of energy as a function of the magnitude of the wave vector for a free electron is a parabola whereas such a plot for an electron wave in the periodic potential of a crystal has a shape similar to that of a valley with flattened edges. The first derivative of this plot represents electron velocity. Similarly, the plot of transmitted frequency as a function of the wave vector for light traveling in a periodically layered arrangement of alternate refractive indices has a shape depicted schematically in the figure. The plot starts as a straight line at small values of k, with its slope denoting the speed of light in the medium. The flattening of the plot at $k \sim \pi/a$ would then indicate slowing of light as the slope becomes small and tends to zero at the boundary. Thus the group velocity of the wave with frequency corresponding to the band edges gets much reduced due to high dispersion. Further, in this case, the high dispersion is not associated with absorption unlike the case of EIT-systems. It is rather easy to incorporate slow-light structures based on photonic crystals in a chip for device applications.

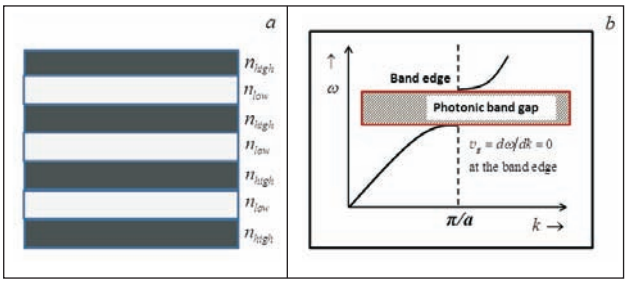

Figure 3A. A periodic arrangement of alternating layers of high and low values of refractive index is shown in (**a**) while (**b**) depicts the formation of photonic band gap in such a photonic crystal with the possibility of obtaining a flat band at the band edge.

[1] K Porsezian and A Joseph, An era of exotic electromagnetism, *Resonance*, Vol.17, No.2, p.163, 2012.

indices of the layers of the structure.

The group of Masaya Natomi *et al* demonstrated slow light ($v_g \sim c/90$) in a 2D-photonic crystal [8]. Slow-light propagation has also been achieved in semiconductor-based photonic crystal slabs and wave guides. They also showed that apart from achieving photonic band gap, it is also important to be able to manipulate the interaction between various modes in the band structure to achieve slow light. The band edges where group velocity vanishes ($d\omega/dk \sim 0$) are called *flat bands* and may be made as flat as desired by appropriate design of the photonic crystal structure. This is crucial as it is the geometry and dimensionality of the photonic crystal that determines the nature of the dispersion relation and shape of the dispersion curve. Light–matter interaction can be expected to get enhanced as interaction time gets larger at the band edges. Flat regions of dispersion relations in photonic crystals are known to be important in achieving or enhancing a variety of effects, including enhancement of the photonic density of states, lasing, enhanced nonlinear effects and other slow-light effects.

The possibility of slowing light down considerably in photonic crystals arises due to backscattering and omnidirectional reflection within the structure. Each unit cell of the photonic crystal, comprising of a region of high and low dielectric constant, acts as a backscattering point and light is coherently scattered, as in a one-dimensional Bragg grating. If the forward and back scattered waves match with each other in phase and amplitude, they form a standing wave implying a slow mode with zero group velocity. Also, a photonic crystal with a complete photonic band-gap structure (which can reflect the light propagating in any angle) can act as an omnidirectional mirror and hence even light propagating at normal incidence can form a mode. Slow-light propagation in photonic crystals is governed by the structure of the optical Brillouin zone. Photonic crystals can be

The possibility of slowing light down considerably in photonic crystals arises due to backscattering and omnidirectional reflection within the structure.

made to function as slow-light structures under appropriate conditions and permit easy incorporation onto a chip by means of lithography at room temperatures.

Two of the most important factors to be considered while designing photonic crystals for attaining slow light are the high order dispersion and the frequency bandwidth. The problem is that the bandwidth gets reduced when we attempt to achieve slow group velocity. Thus the geometry of the device and the material properties of the medium have to be engineered critically to obtain *wide band dispersion-compensated slow light*. The major component of higher order dispersion is *group velocity dispersion* (GVD) which rapidly increases near the band edges. A good compromise between the attainable group velocity and bandwidth is needed for obtaining a desired group velocity in a specific bandwidth region. Higher order dispersion also causes signal distortions and it would be necessary to use strategies aimed at *zero dispersion* slow-light devices or *dispersion-compensated* slow-light devices. Further, high dispersion also limits the bandwidth tunablity. These losses diminish the storage time and interaction length. The study by Kuramochi *et al* reveals a square dependence of loss on the slowdown factor and losses mostly scale as $1/n_g^2$ [9]. The control of intrinsic and extrinsic losses due to structural imperfections occurring in photonic crystals when designed to get slow light is also very challenging. Structural imperfection leads to losses due to diffraction which can affect the process of coherent back scattering in photonic crystals. Despite these problems associated with high dispersion and loss, there is a rapid progress in slow-light technology based on photonic crystals and most of the limitations blocking further advancements in this area have already been solved satisfactorily.

The possibility of slow-light propagation in dielectric structures has opened up several new avenues of potential applications as design of optical memory elements,

The possibility of slow-light propagation in dielectric structures has opened up several new avenues of potential applications as design of optical memory elements, switches and wavelength converters.

While the basic physics of slow light and its interaction with matter are quite intriguing, recent results on the experimental front highlight the scope of photonic-crystal-based slow-light structures for opening up new, efficient and economic avenues of this emerging technology.

switches and wavelength converters. Introducing a delay and controlling the rate of information transfer is rather easy compared to other mechanical methods; thus collision of information carrying light pulses can be avoided. The potential of stopping light altogether allows scope for storing information in optical computing [8, 10]. An interesting simulation to understand the concept of slowing of light, using electronic circuits, has been reported by T Nakanishi *et al* which can be implemented easily in any teaching laboratory [11]. Slowing of light enhances light–matter interaction in materials and can lead to interesting consequences. Slow light can intensify the effects of optical processes such as thermo-optic effect and electro-optic effect considerably. The challenge of the day is to formulate a slow-light technique that can combine high tunablity with low loss. Incorporation of slow-light structures into several linear as well as nonlinear optical devices appears to hold promise for the design of all-optical devices capable for replacing the existing electronic as well as optoelectronic circuitry in control, communication and computing. While the basic physics of slow light and its interaction with matter are quite intriguing, recent results on the experimental front highlight the scope of photonic-crystal-based slow-light structures for opening up new, efficient and economic avenues of this emerging technology.

Suggested Reading

[1] **John S Toll, Causality and the Dispersion Relation: Logical Foundations, *Physical Review*, Vol.104, p.1760, 1956, http://cp.literature.agilent.com/litweb/pdf/5990-5266EN.pdf**

[2] **S L McCall and E L Hahn, Self-induced transparency by pulsed coherent light, *Physical Review Letters*, Vol.18, No.21, p.908, 1967.**

[3] **S E Harris, Electromagnetically induced transparency, *Physics Today*, Vol.50, No.7, p.36, 1997.**

[4] **L V Hau, S E Harris *et al*, Light speed reduction to 17 meter per second in an ultracold atomic gas, *Nature*, Vol.397, p.594, 1999.**

[5] **A Schweinsber *et al*, Observation of superluminal and slow light propagation in erbium-doped optical fiber, *Europhys. Lett.*, Vol.73, p.218, 2006.**

[6] **G M Gehring *et al*, Observation of backward pulse propagation through a medium with a negative group velocity, *Science*, Vol.312, p.895, 2006.**

[7] **A F Koenderink, P M Johnson, J F G Lopez and W L Vos, Three-dimensional photonic crystals as cage for light, *C R Physique*, Vol.3, p.67, 2002.**

[8] **M Notomi, Manipulating light with strongly modulated photonic crystals, *Rep. Prog. Phys*., Vol.73, 096501, p.57, 2010.**

[9] **E Kuramochi, M Natomi, S Hughes, A Shinya, T Watanabe and L Ramunno, Disorder-induced scattering loss of line-defect waveguides in photonic crystal slabs, *Phys. Rev. B*, Vol.72, 161318(R), p.1, 2005.**

[10] **R Boyd and D J Gautheir, Controlling the velocity of light, *Science*, Vol.326, p.1074, 2009.**

[11] **T Nakanishi, K Sugiyama and M Kitano, Simulation of slow light with electronic circuits, *Am. J. Phys*, Vol.73, No.4, p.323, 2005.**

Address for Correspondence
C Vijayan
Department of Physics
Indian Institute of Technology, Madras
Chennai 600 036, India.
Email:
cvijayan@physics.iitm.ac.in