Lec 35: Photonic Crystal Devices for Slow Wave Phenomena

Photonic Crystals:
Fundamentals and Applications

Lecture 35

Photonic Crystal Devices for Slow Wave Phenomena

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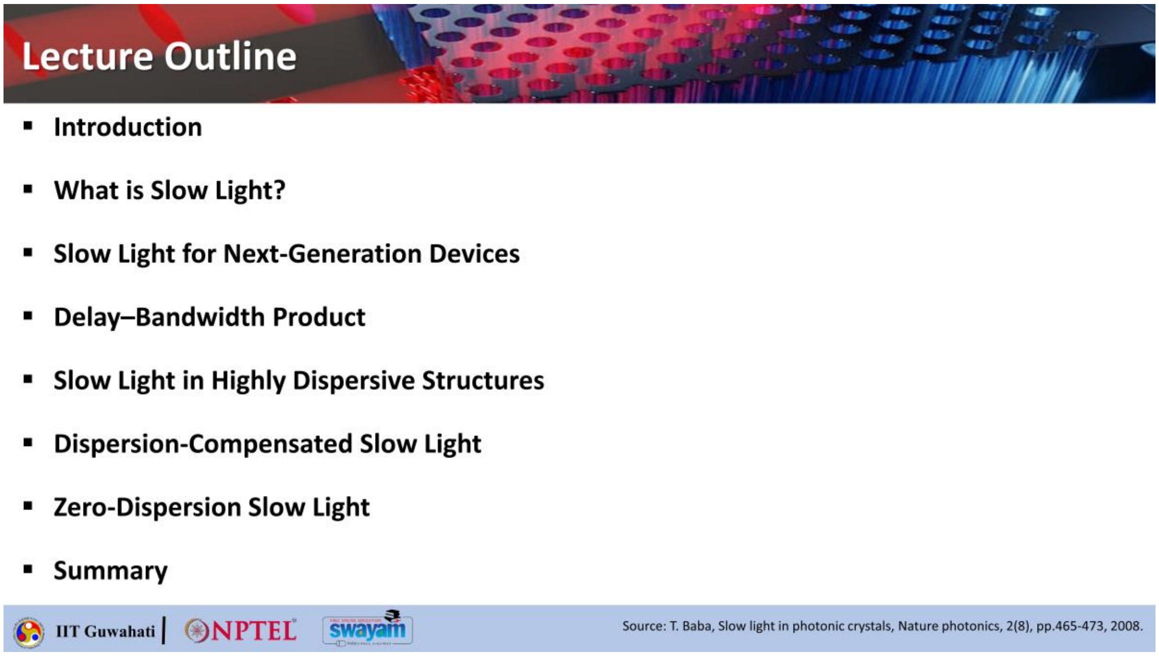
Hello students, welcome to lecture 35 of the online course on Photonic Crystals Fundamentals and Applications.



Lecture Outline

- Introduction
- What is Slow Light?
- Slow Light for Next-Generation Devices
- Delay–Bandwidth Product
- Slow Light in Highly Dispersive Structures
- Dispersion-Compensated Slow Light
- Zero-Dispersion Slow Light
- Summary

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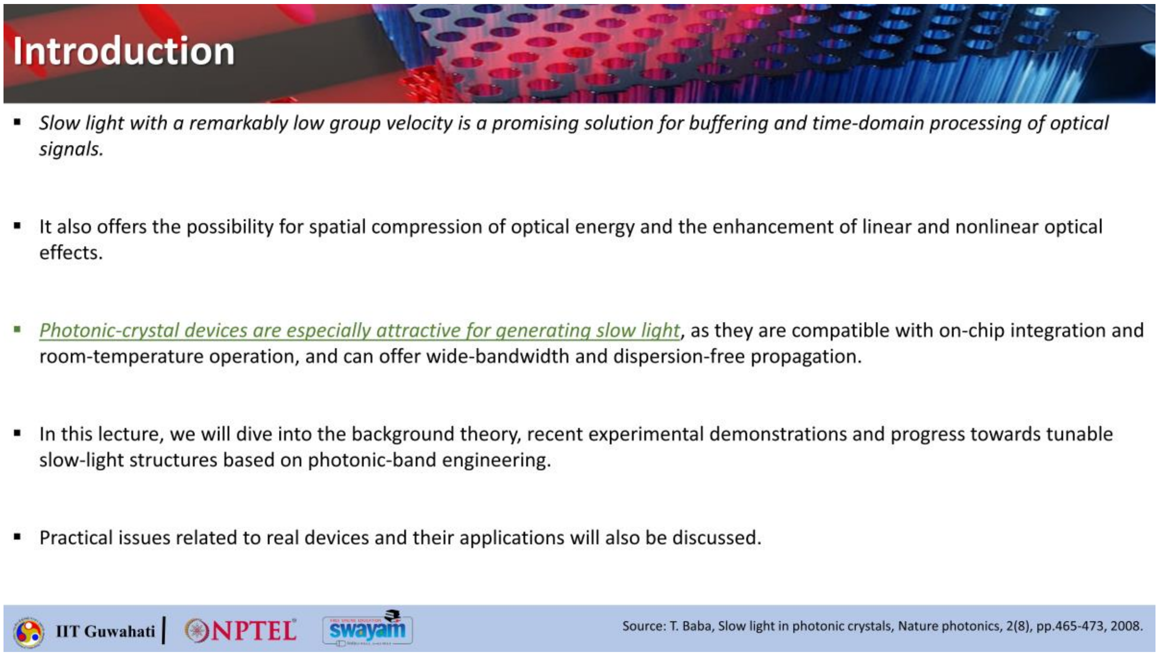
Source: T. Baba, Slow light in photonic crystals, Nature photonics, 2(8), pp.465-473, 2008.

Today's lecture we will be discussing about photonic crystal devices for slow wave phenomena. So, here is the lecture outline, we will have a brief introduction to the topic, we will discuss what is slow light, we will find out the applications of slow light in next generation devices Then we will calculate the delay bandwidth product, we will discuss about slow light in highly dispersive structures, dispersion compensated slow light, zero dispersion slow light and finally we will conclude okay this particular topic.



Introduction

- *Slow light with a remarkably low group velocity is a promising solution for buffering and time-domain processing of optical signals.*
- It also offers the possibility for spatial compression of optical energy and the enhancement of linear and nonlinear optical effects.
- *Photonic-crystal devices are especially attractive for generating slow light*, as they are compatible with on-chip integration and room-temperature operation, and can offer wide-bandwidth and dispersion-free propagation.
- In this lecture, we will dive into the background theory, recent experimental demonstrations and progress towards tunable slow-light structures based on photonic-band engineering.
- Practical issues related to real devices and their applications will also be discussed.

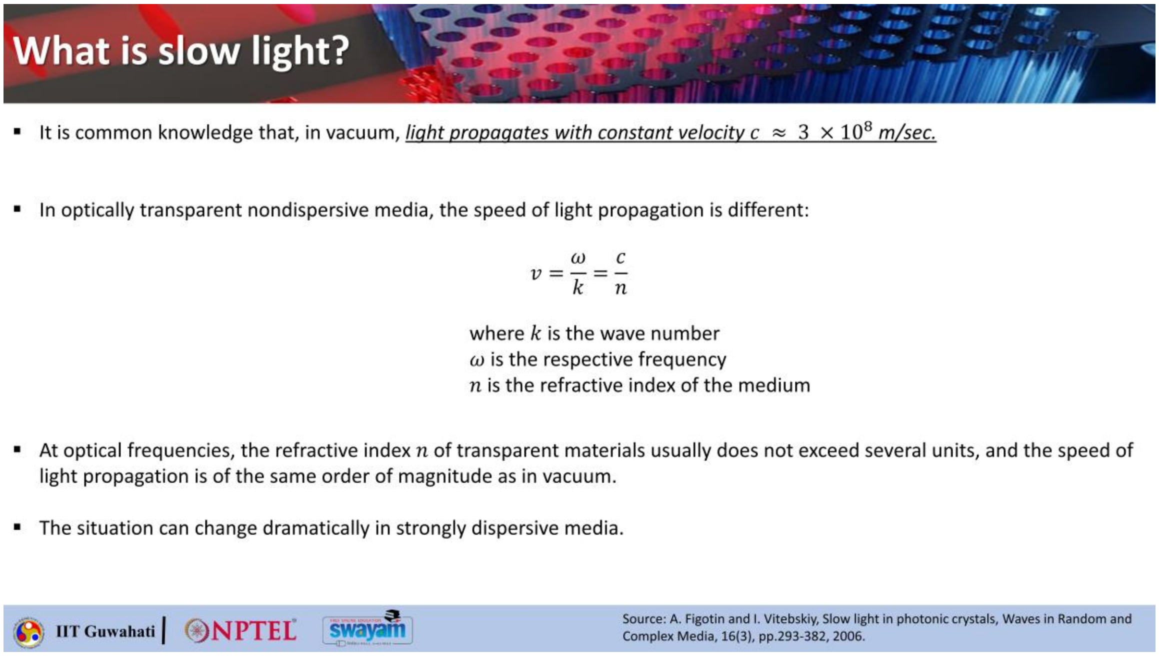
Source: T. Baba, Slow light in photonic crystals, Nature photonics, 2(8), pp.465-473, 2008.

What is slow light? Slow light with a remarkably low group velocity is a promising solution for buffering and time domain processing of optical signals. So, as you can understand it is slow. So, when I say slow light it means it is a light which has got very low group velocity.

So, it also offers the possibility for spatial compression of optical energy and the enhancement of linear and non-linear optical effects. Photonic crystal devices are especially attractive for generating slow light. as they are compatible with on-chip integration and room temperature operation. Thus, they are also able to offer wide bandwidth and dispersion free propagation.

What is Slow Light?

In this lecture, we will dive into the background theory, discuss about some recent experimental demonstrations and progress made towards tunable slow light structures based on photonic band engineering. And the practical issues related to the real device and their applications will also be discussed in this lecture. So, what is slow light?



What is slow light?

- It is common knowledge that, in vacuum, *light propagates with constant velocity $c \approx 3 \times 10^8$ m/sec.*
- In optically transparent nondispersive media, the speed of light propagation is different:

$$v = \frac{\omega}{k} = \frac{c}{n}$$

where k is the wave number
ω is the respective frequency
n is the refractive index of the medium

- At optical frequencies, the refractive index n of transparent materials usually does not exceed several units, and the speed of light propagation is of the same order of magnitude as in vacuum.
- The situation can change dramatically in strongly dispersive media.

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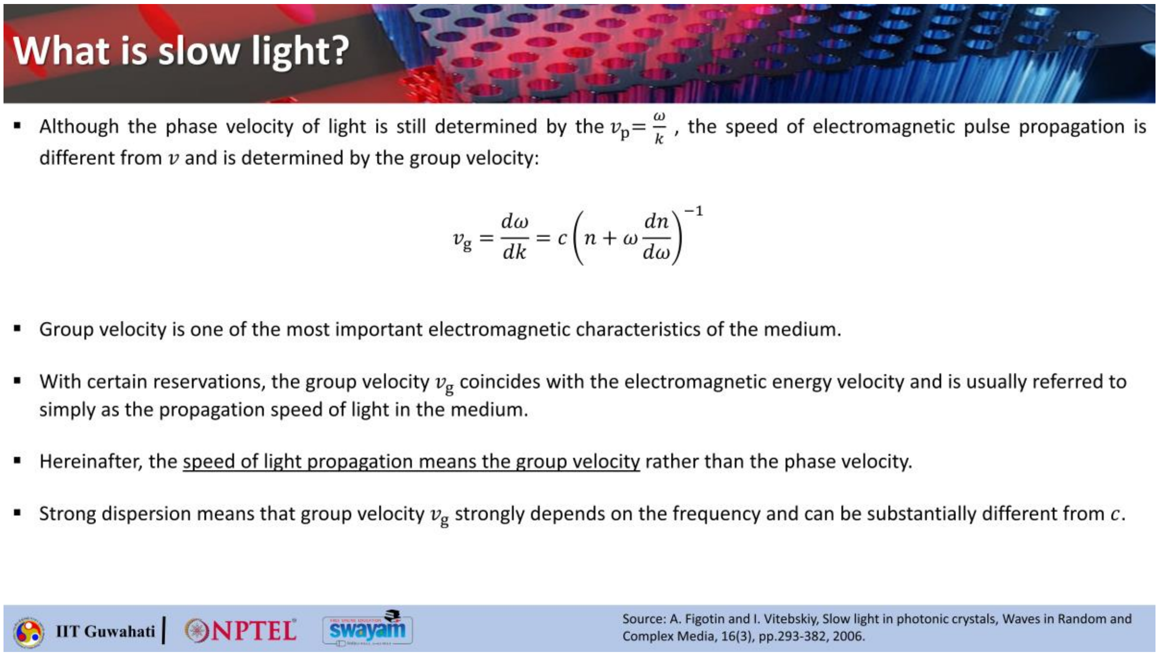
Source: A. Figotin and I. Vitebskiy, Slow light in photonic crystals, Waves in Random and Complex Media, 16(3), pp.293-382, 2006.

So, let us go into the background of light and we all have been knowing this from our school days that you know in vacuum light propagates with a constant velocity c that is equivalent to 3×10^8 meter per second. In optically transparent non-dispersive media, the speed of light propagation is different and the speed is not c, it is rather v and v equals ω/k that is equal to c/n. So, what is ω? That is the respective angular frequency, k is the wave number.

or yeah k is the wave number and that this ratio ω/k ratio is equivalent to c/n, c is the speed of light in vacuum and n is the refractive index of that medium. So, larger the refractive index slower will be the velocity of light. At optical frequencies the refractive index n of transparent materials usually do not exceed several units and hence the speed of light propagation is typically of the same order of magnitude as it is in vacuum.

So, if you consider glass, glass is a transparent medium which has got a refractive index of 1.55. So, n is 1.55. So, you can understand that v is more or less of the order of c. So, that is not the case when we are getting slow light. the situation this particular situation can change dramatically in the case of strongly dispersive media.



What is slow light?

- Although the phase velocity of light is still determined by the $v_p = \frac{\omega}{k}$, the speed of electromagnetic pulse propagation is different from v and is determined by the group velocity:

$$v_g = \frac{d\omega}{dk} = c\left(n + \omega\frac{dn}{d\omega}\right)^{-1}$$

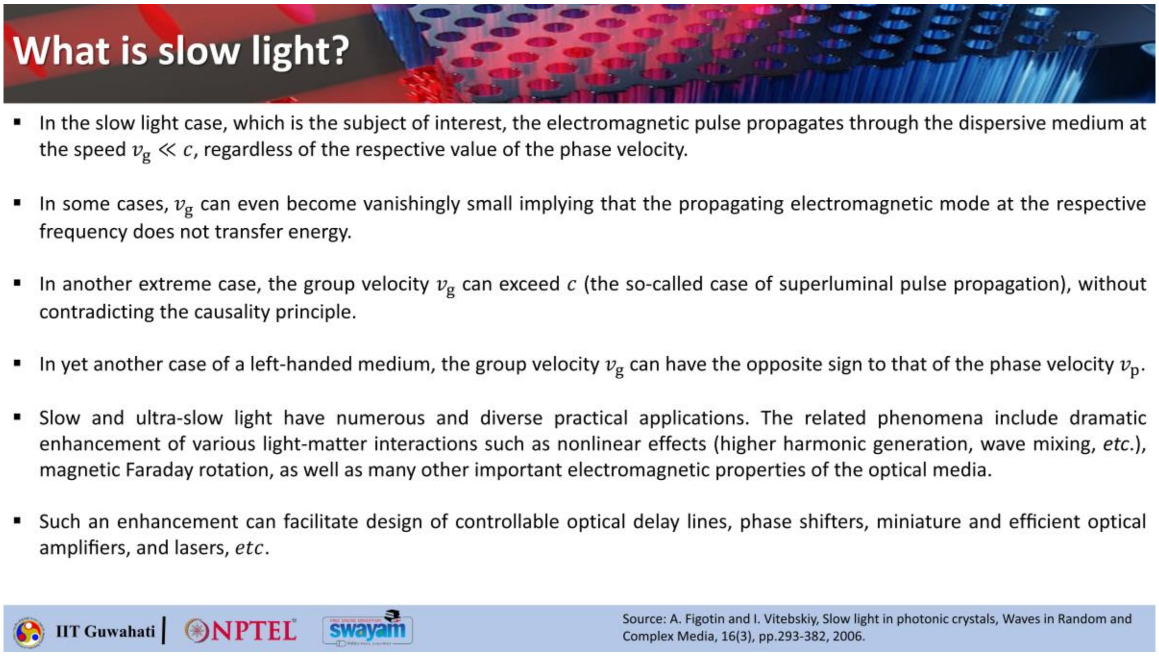
- Group velocity is one of the most important electromagnetic characteristics of the medium.
- With certain reservations, the group velocity v_g coincides with the electromagnetic energy velocity and is usually referred to simply as the propagation speed of light in the medium.
- Hereinafter, the speed of light propagation means the group velocity rather than the phase velocity.
- Strong dispersion means that group velocity v_g strongly depends on the frequency and can be substantially different from c.

Source: A. Figotin and I. Vitebskiy, Slow light in photonic crystals, Waves in Random and Complex Media, 16(3), pp.293-382, 2006.

So, in that case although you know the phase velocity of the light is determined by you know v_p equals $\omega/$k the speed of the electromagnetic pulse propagation. So, that is basically determined by the group velocity. So, that is $d\omega/d$k. and that is significantly different from the velocity v. So, pulse has got different frequency components that is why it is a group ok.

The phase velocity is typically for only a single frequency. So, it is the phase velocity v_p. So, v_g is the group velocity that can be written as $d\omega/d$k can also be expanded in this particular form. So, group velocity is one of the most important electromagnetic characteristics of the medium. So, with certain reservations you will see that the group velocity v_g coincides with the electromagnetic energy velocity and is therefore, typically you know referred to as the propagation of light in the medium or propagation speed of light in the medium.

So, group velocity determines the speed of electromagnetic energy flow. So, that is basically the propagation speed of light in medium. So, whenever wherever we are talking about the speed of light propagation we are basically referring to the group velocity not the phase velocity. So, strong dispersion means that the group velocity v_g strongly depends on the frequency and can be substantially different from c.



What is slow light?

- In the slow light case, which is the subject of interest, the electromagnetic pulse propagates through the dispersive medium at the speed $v_{\mathrm{g}} \ll c$, regardless of the respective value of the phase velocity.
- In some cases, v_{g} can even become vanishingly small implying that the propagating electromagnetic mode at the respective frequency does not transfer energy.
- In another extreme case, the group velocity v_{g} can exceed c (the so-called case of superluminal pulse propagation), without contradicting the causality principle.
- In yet another case of a left-handed medium, the group velocity v_{g} can have the opposite sign to that of the phase velocity v_{p}.
- Slow and ultra-slow light have numerous and diverse practical applications. The related phenomena include dramatic enhancement of various light-matter interactions such as nonlinear effects (higher harmonic generation, wave mixing, *etc.*), magnetic Faraday rotation, as well as many other important electromagnetic properties of the optical media.
- Such an enhancement can facilitate design of controllable optical delay lines, phase shifters, miniature and efficient optical amplifiers, and lasers, *etc*.

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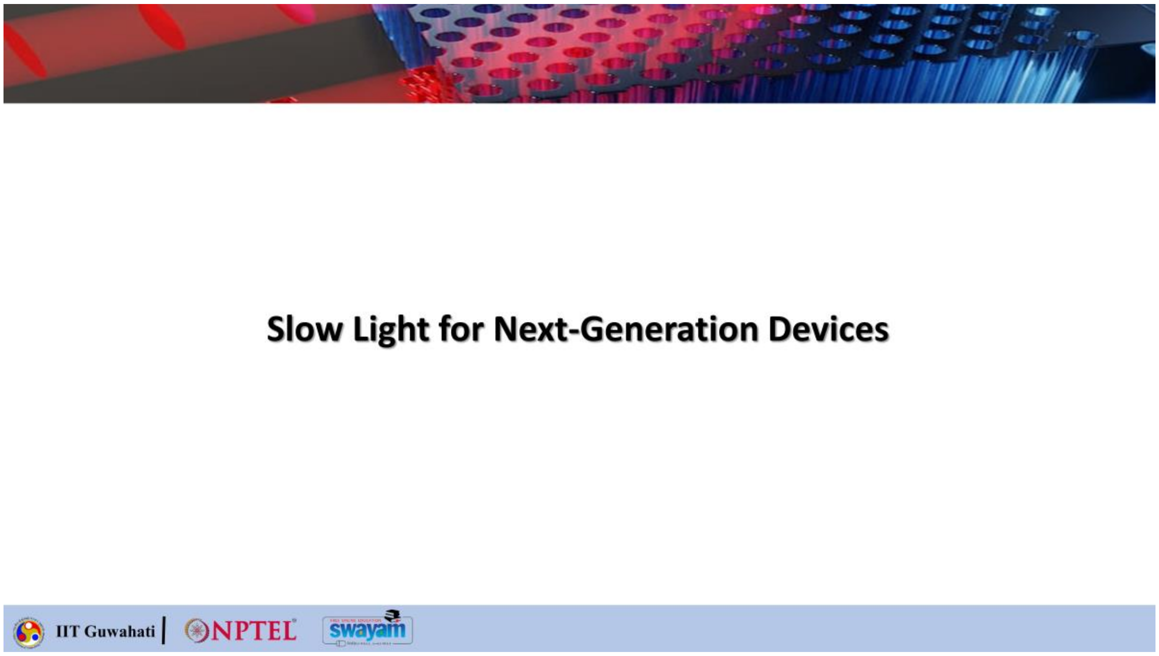
Source: A. Figotin and I. Vitebskiy, Slow light in photonic crystals, Waves in Random and Complex Media, 16(3), pp.293-382, 2006.

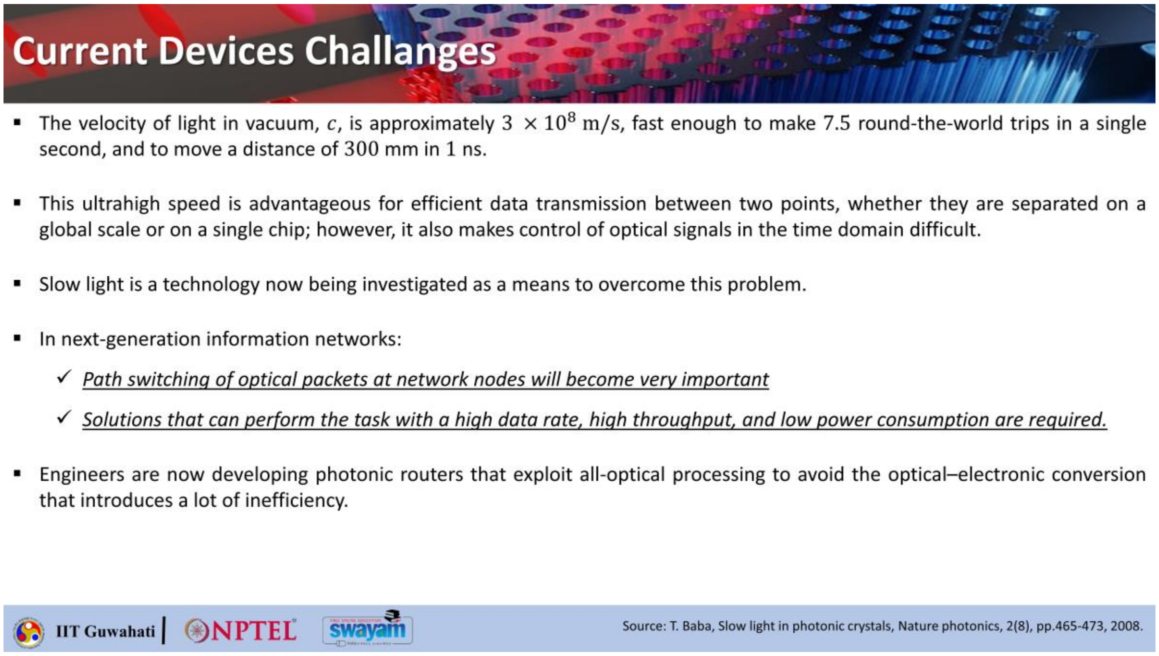
So, in the case of slow light which is the subject of interest in this particular lecture, the electromagnetic pulse propagates through the dispersive medium at a speed which is v_g much much slower than the speed of light in vacuum that is c regardless of the you know respective value of phase velocity.

So, in some cases v_g can become vanishingly small implying that the electromagnetic you know mode is basically propagating at a very slow speed okay and at that respective frequency it does not transfer energy. So, in another extreme case where the group velocity vg can also exceed c and that is the case of so called you know superluminal pulse propagation. So, and that can happen without contradicting the causality principle. And yet another case of the left handed medium the group velocity v_g can have the opposite sign of that of the phase velocity v_p ok. So, all these interesting possibilities are there.

So, slow and ultra slow light have numerous practical applications. The related phenomena something like you know dramatic enhancement of light matter interaction such as the nano scale non-linear effects, something like higher harmonic generation, wave mixing etcetera can happen. Magnetic Faraday rotation as well as other electromagnetic properties of the optical media can also be exploited. So, such an enhancement can facilitate the design of controllable optical delay lines. ok, phase shifter, miniature and efficient optical amplifiers and lasers ok.



Slow Light for Next-Generation Devices



Current Devices Challanges

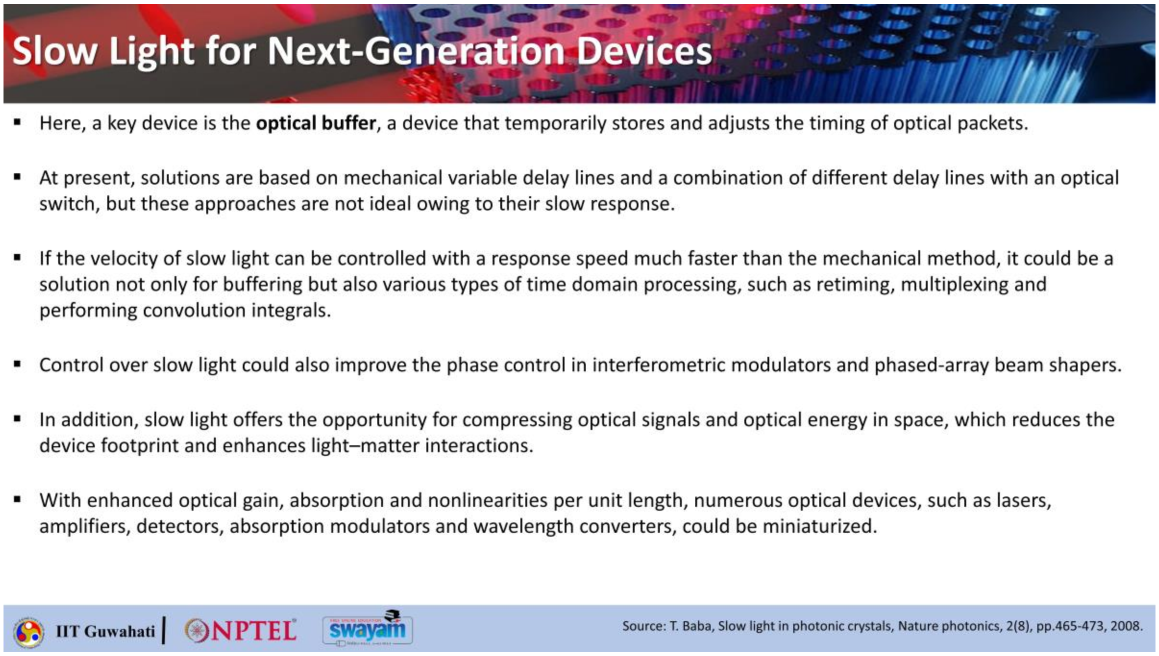
- The velocity of light in vacuum, c, is approximately 3×10^{8} m/s, fast enough to make 7.5 round-the-world trips in a single second, and to move a distance of 300 mm in 1 ns.
- This ultrahigh speed is advantageous for efficient data transmission between two points, whether they are separated on a global scale or on a single chip; however, it also makes control of optical signals in the time domain difficult.
- Slow light is a technology now being investigated as a means to overcome this problem.
- In next-generation information networks:
  - ✓ *Path switching of optical packets at network nodes will become very important*
  - ✓ *Solutions that can perform the task with a high data rate, high throughput, and low power consumption are required.*
- Engineers are now developing photonic routers that exploit all-optical processing to avoid the optical–electronic conversion that introduces a lot of inefficiency.

Source: T. Baba, Slow light in photonic crystals, Nature photonics, 2(8), pp.465-473, 2008.

So, in addition the ultra slow light might allow non-linear interactions down to a single photon level which could significantly benefit the design of ultra sensitive optical switches, quantum all optical data storage and data processing devices. So, ultra slow light can also be used in quantum communication and design of novel acousto-optical devices. So, now let us look into slow light for next generation devices. So, what are the current devices device challenges? So, you can see that the velocity of light in vacuum is c that is you know 3×10^{8} meter per second. It is like basically fast enough to make 7 and half round around the world in a single second or you can say it can move 300 millimeter in one nanosecond ok. So, that is the tremendous speed of light. So, this ultra high speed is advantages for efficient data communication between two points ok. So, which are like you know separated by global scale right or on a single chip. you can use the speed of light for communication.

However, it makes now control of optical signals in the time domain very difficult because of this very fast speed. So, slow light is basically a technology now being investigated as a means to overcome this problem so that you can achieve control over light signal in the time domain itself. So, next generation information networks. The path switching of optical packets at network nodes will become very important and solutions that can perform the task with a high data rate, high throughput and also low power consumptions are required. So, these are the two important things okay which is required for the next generation information networks.

So, engineers are now developing photonic routers that exploit all optical processing that can avoid the electrical optical conversion and that also you know this conversion basically introduces a lot of inefficiency.



Slow Light for Next-Generation Devices

- Here, a key device is the **optical buffer**, a device that temporarily stores and adjusts the timing of optical packets.
- At present, solutions are based on mechanical variable delay lines and a combination of different delay lines with an optical switch, but these approaches are not ideal owing to their slow response.
- If the velocity of slow light can be controlled with a response speed much faster than the mechanical method, it could be a solution not only for buffering but also various types of time domain processing, such as retiming, multiplexing and performing convolution integrals.
- Control over slow light could also improve the phase control in interferometric modulators and phased-array beam shapers.
- In addition, slow light offers the opportunity for compressing optical signals and optical energy in space, which reduces the device footprint and enhances light–matter interactions.
- With enhanced optical gain, absorption and nonlinearities per unit length, numerous optical devices, such as lasers, amplifiers, detectors, absorption modulators and wavelength converters, could be miniaturized.

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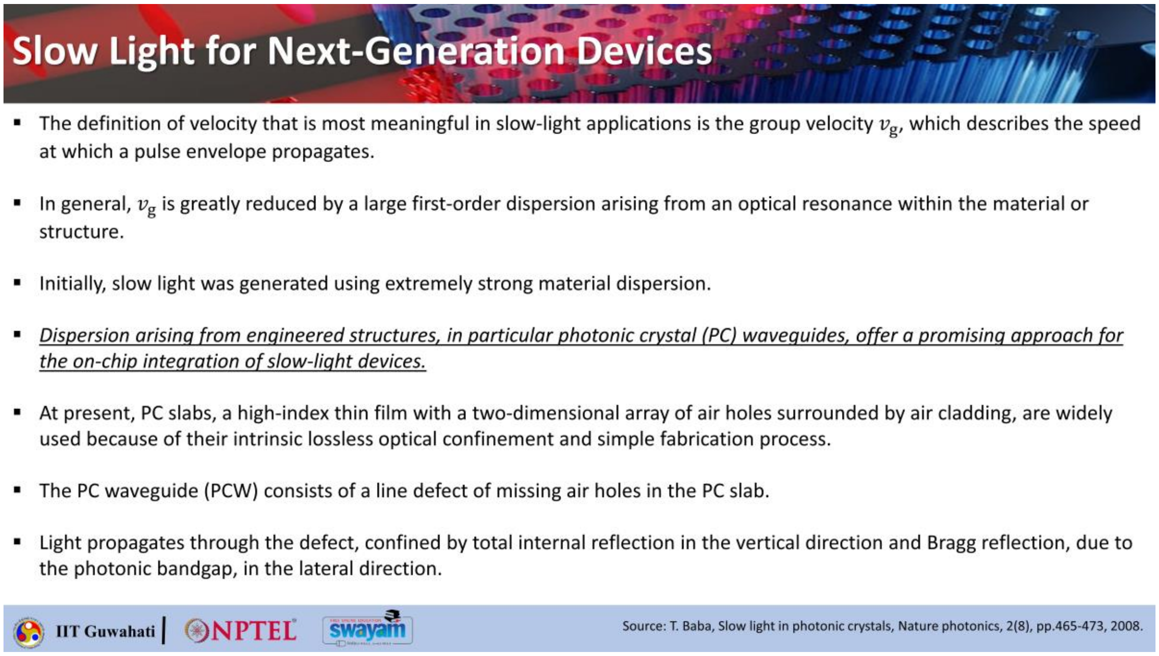
Source: T. Baba, Slow light in photonic crystals, Nature photonics, 2(8), pp.465-473, 2008.

So, here a key device is the optical buffer that is basically a device that temporarily stores and adjusts the timing of optical packets. At present the solutions are based on mechanical variable delay line and a combination of different delay lines with an optical switch. okay but this approaches are not ideal going to their slow response okay anything mechanical will time take time to adjust right. So, if the velocity of slow light can be controlled with a response speed much faster than this traditional mechanical methods it could be a solution that can be used not only for buffering but also for various types of time domain processing something like retiming, multiplexing and performing convolutional integrals.

So, what we understood that the control of slow light could improve the phase control in interferometric modulators and phased array beam shapers. In addition, slow light offers the opportunity for compressing optical signals and optical energy in space, which would basically help you to reduce the device footprint and also enhance the light matter interaction. So, with enhanced optical gain absorption and non-linearities per unit length, numerous optical devices such as lasers, amplifiers, detectors, modulators, wavelength converters all these devices can be miniaturized.



Slow Light for Next-Generation Devices

- The definition of velocity that is most meaningful in slow-light applications is the group velocity v_g, which describes the speed at which a pulse envelope propagates.
- In general, v_g is greatly reduced by a large first-order dispersion arising from an optical resonance within the material or structure.
- Initially, slow light was generated using extremely strong material dispersion.
- *Dispersion arising from engineered structures, in particular photonic crystal (PC) waveguides, offer a promising approach for the on-chip integration of slow-light devices.*
- At present, PC slabs, a high-index thin film with a two-dimensional array of air holes surrounded by air cladding, are widely used because of their intrinsic lossless optical confinement and simple fabrication process.
- The PC waveguide (PCW) consists of a line defect of missing air holes in the PC slab.
- Light propagates through the defect, confined by total internal reflection in the vertical direction and Bragg reflection, due to the photonic bandgap, in the lateral direction.

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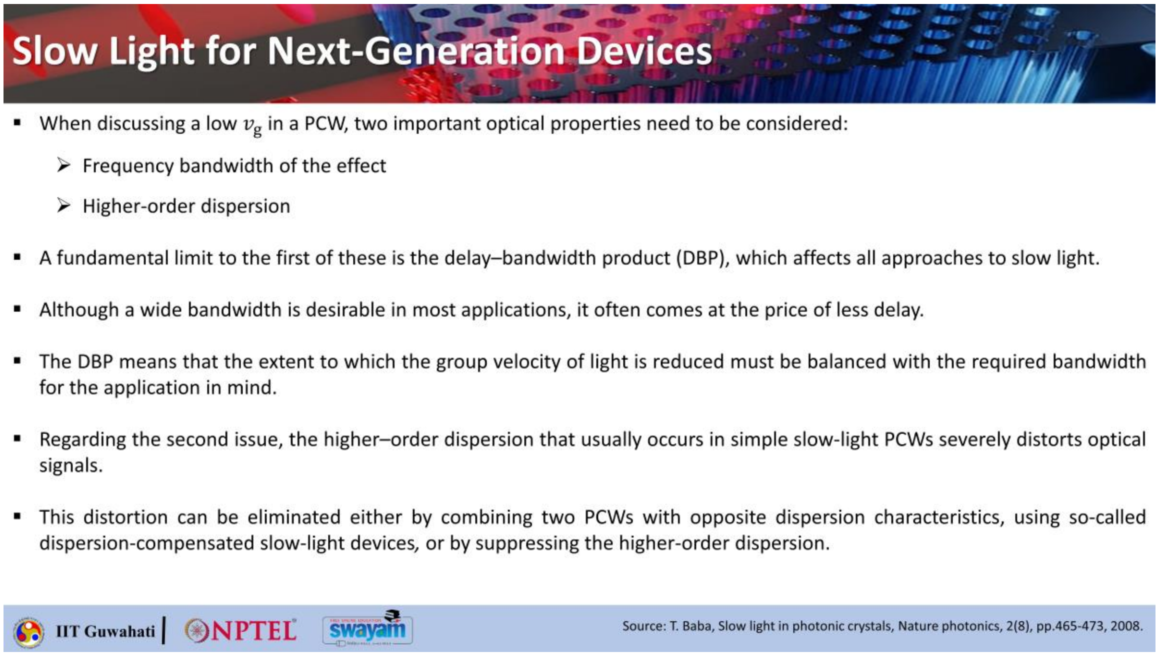
Source: T. Baba, Slow light in photonic crystals, Nature photonics, 2(8), pp.465-473, 2008.

So, that is basically setting up the platform for you know compact devices. The definition of velocity that is most meaningful in the case of slow light application is the group velocity v_g which basically describes the speed of envelope okay in which the pulse propagates.

or you can say this basically describes the speed of pulse envelope propagation right. So, in general v_g is greatly reduced by a large first order dispersion arising from an optical resonance within the material or the structure itself. So, initially slow light was generated with extremely strong material dispersion. Now, material dispersion is basically a phenomena that occurs when different optical wavelengths travel at different speeds through a particular material. Dispersion arising from engineered structures such as you know photonic crystal waveguides can offer promising solutions towards on chip integration of the slow light devices.

So at present photonic crystal slabs a high index thin film with a two dimensional area of air holes surrounded by air cladding. So we have seen this structure many many times in this course. They are widely used because of their intrinsic lossless optical confinement and relatively simple fabrication process. So, the photonic crystal waveguide or PCW, it consists of a line defect of missing air holes in the photonic crystal slab okay.



Slow Light for Next-Generation Devices

- When discussing a low v_g in a PCW, two important optical properties need to be considered:
  - Frequency bandwidth of the effect
  - Higher-order dispersion
- A fundamental limit to the first of these is the delay–bandwidth product (DBP), which affects all approaches to slow light.
- Although a wide bandwidth is desirable in most applications, it often comes at the price of less delay.
- The DBP means that the extent to which the group velocity of light is reduced must be balanced with the required bandwidth for the application in mind.
- Regarding the second issue, the higher–order dispersion that usually occurs in simple slow-light PCWs severely distorts optical signals.
- This distortion can be eliminated either by combining two PCWs with opposite dispersion characteristics, using so-called dispersion-compensated slow-light devices, or by suppressing the higher-order dispersion.

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Source: T. Baba, Slow light in photonic crystals, Nature photonics, 2(8), pp.465-473, 2008.

Try to imagine the structure, we will show it in the next slide okay.

So, the light propagates through the defect confined by the total internal reflection in the vertical direction and Bragg reflection due to the photonic band gap in the lateral dimension. So it has been known since 2001 the strong dispersion in this waveguide generates slow light in the vicinity of the photonic band edge okay. So when discussing a low group velocity v_g in a photonic crystal waveguide two important optical properties need to be considered first. the frequency bandwidth of the effect and second the higher order dispersion. So, a fundamental limit to the first of these is the delay bandwidth product or DPB, DBP, delay bandwidth product which affects all approaches to slow light.

Although a wide bandwidth is desirable in most of the application, but usually it often comes with the price of less delay. So, the DBP means means the Delayed Bandwidth Product means that the extent to which your group velocity is reduced must be balanced by must be balanced with the required bandwidth for the application that you are considering. And regarding the second issue that is you know higher order dispersion that usually occurs in simple slow light photonic crystal waveguides okay that could severely distort optical signals. And this distortion can be eliminated either by combining two PCWs of opposite dispersion characteristics. So, these are basically called dispersion compensated slow light devices or by suppressing the higher order dispersion itself.

Delay–Bandwidth Product

Delay–Bandwidth Product

Delay-Bandwidth Product

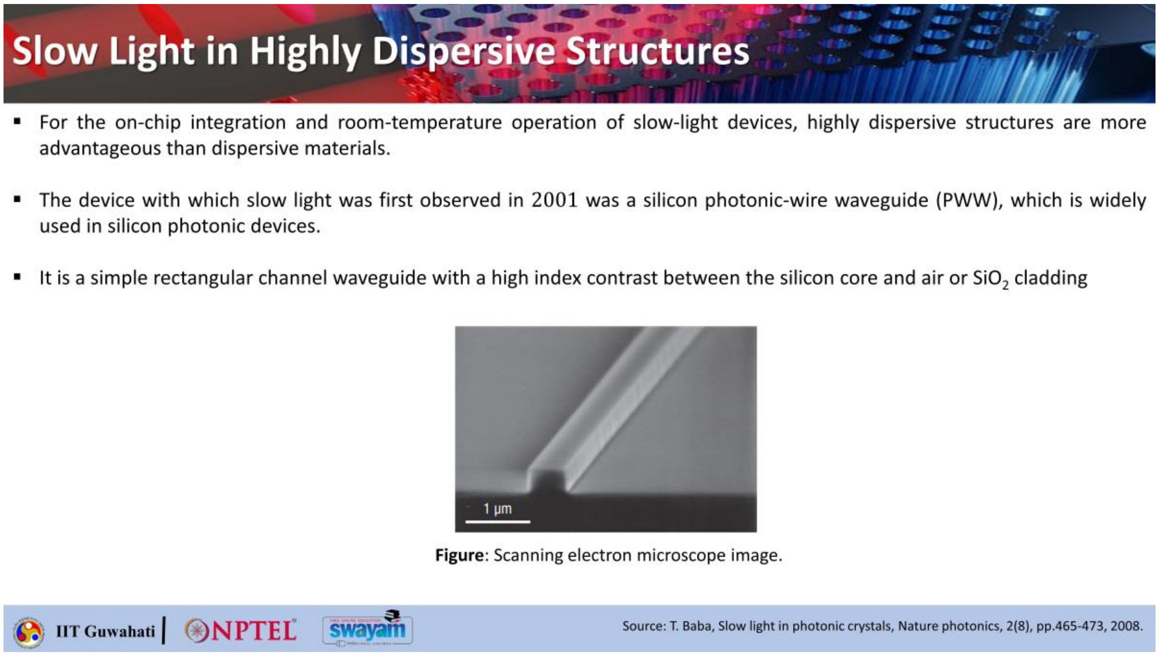
- The concept of delay-bandwidth Product (DBP) is a good indication for the highest slow light capacity that the device potentially provides.
- DBP is defined as: $\mathrm{DBP} = \Delta t \times \Delta f$
- Δt is the delay of light at a wavelength λ over a propagation length of L.
- Δf is the frequency bandwidth centered at a frequency of $f = \omega/2\pi$.
- The time duration of one optical bit is approximately given by Δf^{-1}, although an accurate value depends on the modulation format.
- Therefore, the DBP is a good indication of the highest buffering capacity that the slow-light device potentially provides.

Source: T. Baba, Slow light in photonic crystals, Nature photonics, 2(8), pp.465-473, 2008.

So, now we look into the calculation of delay bandwidth product in more details. So, the concept of delay bandwidth product is a good indication for the highest slow light capacity that the device potentially could provide. So, DBP can be calculated as delay into bandwidth that is Δt × Δf okay. So, Δt is basically the delay of light at a wavelength lambda over a propagation length of L and what is Δf that is the frequency bandwidth centered at a frequency f which is nothing but $\frac{\omega}{2\pi}$ okay this one. So, the time duration of one optical bit is approximately given by you know Δf inverse although an accurate value could depend on the modulation format that you are using. Therefore, the delay bandwidth product is a good indication of the highest buffering capacity that the slow light device potentially provides.

On the other hand, the normalized form can be more useful when devices that have different lengths and different operating frequencies are basically compared.

Slow Light in Highly Dispersive Structures



Slow Light in Highly Dispersive Structures

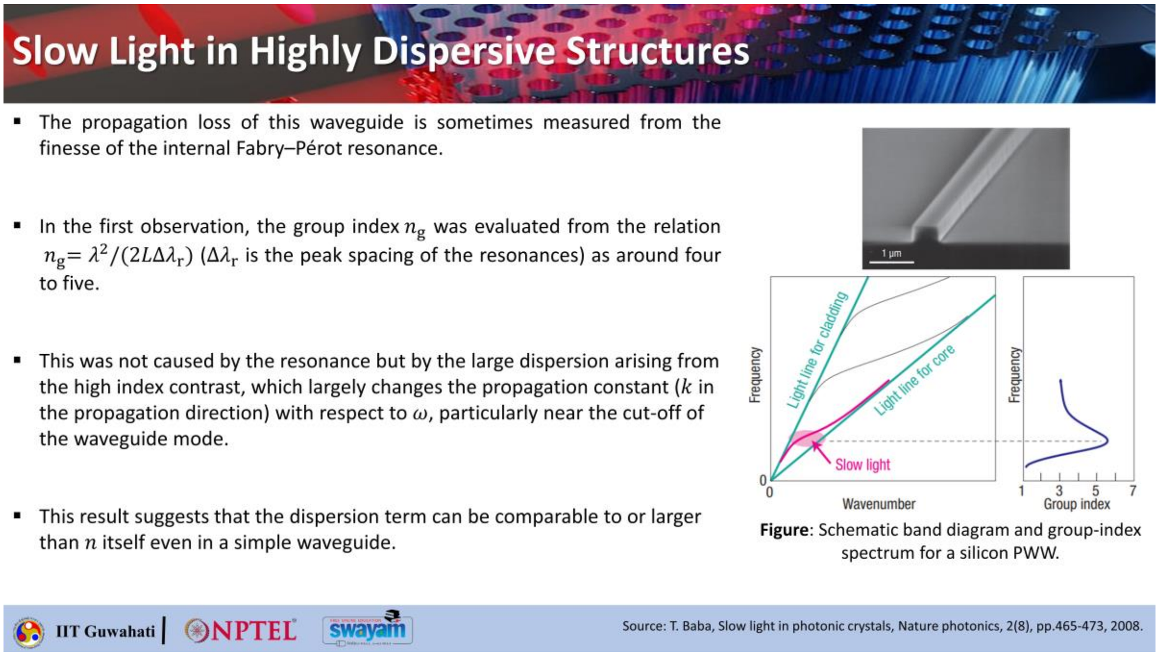
- For the on-chip integration and room-temperature operation of slow-light devices, highly dispersive structures are more advantageous than dispersive materials.
- The device with which slow light was first observed in 2001 was a silicon photonic-wire waveguide (PWW), which is widely used in silicon photonic devices.
- It is a simple rectangular channel waveguide with a high index contrast between the silicon core and air or SiO_2 cladding

Figure: Scanning electron microscope image.

Source: T. Baba, Slow light in photonic crystals, Nature photonics, 2(8), pp.465-473, 2008.

Now, we will look into slow light in highly dispersive structures. For the on-chip integration and room temperature operation of slow light devices, highly dispersive structures are more advantages than dispersive materials. The device with which slow light was first observed in 2001 was a silicon photonic wear waveguide.

So, you can call it as PWW photonic wear waveguide which is basically a widely used device in silicon photonics right. So, this is the scanning microscope image of that device. photonic wear waveguide okay. So, it is basically a simple rectangular channel waveguide with a high index contrast between the silicon core and air or if there is you know silica cladding.



Slow Light in Highly Dispersive Structures

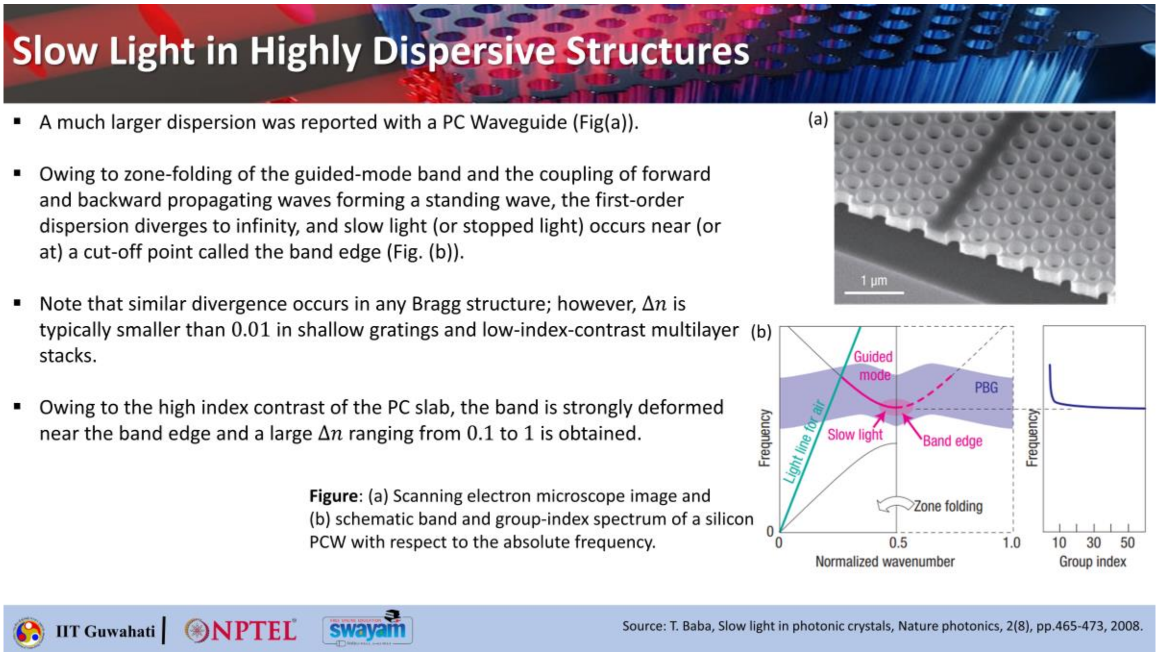
- The propagation loss of this waveguide is sometimes measured from the finesse of the internal Fabry–Pérot resonance.
- In the first observation, the group index n_{g} was evaluated from the relation $n_{\mathrm{g}} = \lambda^2/(2L\Delta\lambda_{\mathrm{r}})$ ($\Delta\lambda_{\mathrm{r}}$ is the peak spacing of the resonances) as around four to five.
- This was not caused by the resonance but by the large dispersion arising from the high index contrast, which largely changes the propagation constant (k in the propagation direction) with respect to ω, particularly near the cut-off of the waveguide mode.
- This result suggests that the dispersion term can be comparable to or larger than n itself even in a simple waveguide.

Figure: Schematic band diagram and group-index spectrum for a silicon PWW.

Source: T. Baba, Slow light in photonic crystals, Nature photonics, 2(8), pp.465-473, 2008.

So, the propagation loss of this waveguide is sometimes measured from the fineness of the internal Fabry-Perot resonance.

So, in the first observation you can say that the group index n_g was evaluated from the relationship this one n_g equals $\lambda^2/(2L\Delta\lambda_{\mathrm{r}})$ where λ_{r} is basically the peak spacing of the resonances ok. So, these are the wavelength difference between the resonance peaks ok as around 4 to 5 ok and This was not caused by the resonance, but by the large dispersion that is arising from the high index contrast between the core and the cladding okay, which largely changes the propagation constant that is k in the propagation direction with respect to omega particularly near the cutoff of the waveguide mode. So, here you can see the schematic band diagram and the group index spectrum of the silicon photonic wire waveguide and this particular straight line shows the light line for the cladding So, this can be air or this can be silica ok. So, we are not mentioning which one is this exactly and this is for the core ok and these are some of those guided modes and what you can see here you can see that something So, this region is basically giving the slow light which has got a very high group index, okay. So, this results suggest that the dispersion term can be comparable to or larger than n itself even in simple waveguide.



Slow Light in Highly Dispersive Structures

- A much larger dispersion was reported with a PC Waveguide (Fig(a)).
- Owing to zone-folding of the guided-mode band and the coupling of forward and backward propagating waves forming a standing wave, the first-order dispersion diverges to infinity, and slow light (or stopped light) occurs near (or at) a cut-off point called the band edge (Fig. (b)).
- Note that similar divergence occurs in any Bragg structure; however, Δn is typically smaller than 0.01 in shallow gratings and low-index-contrast multilayer stacks.
- Owing to the high index contrast of the PC slab, the band is strongly deformed near the band edge and a large Δn ranging from 0.1 to 1 is obtained.

Figure: (a) Scanning electron microscope image and (b) schematic band and group-index spectrum of a silicon PCW with respect to the absolute frequency.

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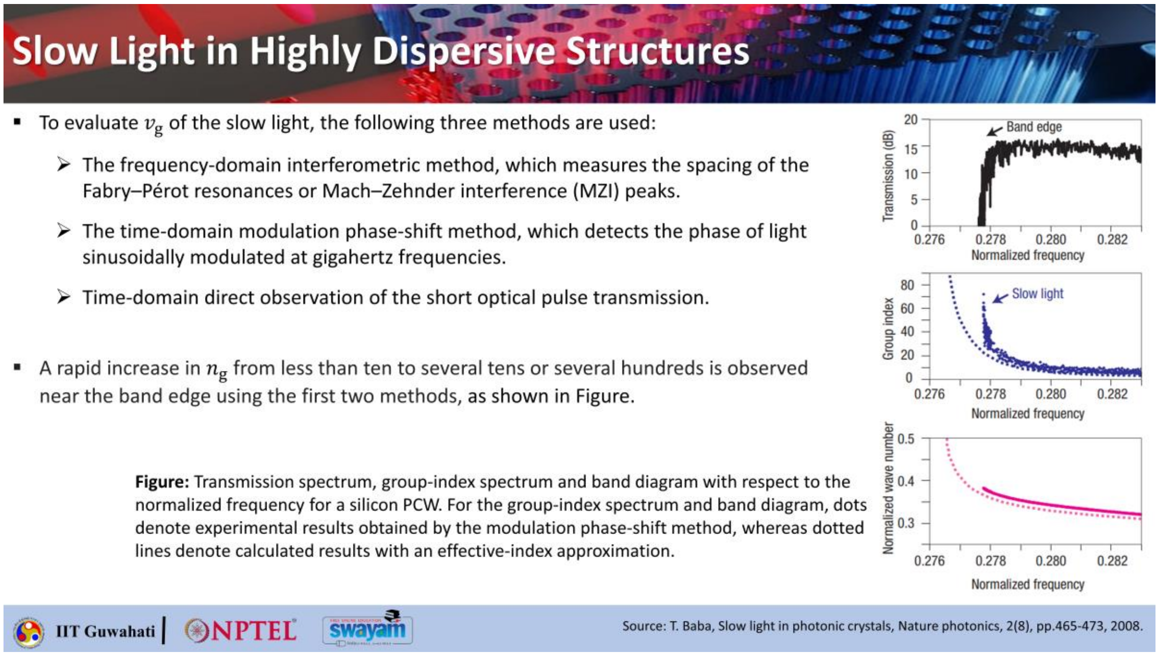
Source: T. Baba, Slow light in photonic crystals, Nature photonics, 2(8), pp.465-473, 2008.

Now, if you go for a more complicated waveguide that is made of a photonic crystal waveguide, like this you can have much larger dispersion okay. So, what you see here this is the electron scanning electron microscope image of the waveguide which is made on a photonic crystal slab and this shows the schematic band diagram and the group index spectrum of this photonic crystal waveguide with respect to the frequency. So, you have frequency on this particular axis and these are the group index and normalized wave number. So, what you see there is zone folding here. So, because of the so only this part is calculated and this will be the folded version of it that you have seen earlier also.

so going to the zone folded what happens this this particular line shows the light line ok for air and this is the guided mode. So, what you see that owing to zone folding of the guided mode band and the coupling of the forward and the backward propagating waves it basically. So, this is one is this way another is this way. So, they basically forward and backward and they form a standing wave ok. the first order dispersion basically diverges to infinity and the slow light or in this case you can say stopped light occurs near or exactly at the cutoff point which is also called the bend edge over here okay.

Note that a similar divergence also occurs in any Bragg structure. However, delta n is typically smaller than 0.01 in shallow gratings and low index contrast multilayer stacks. So owing to the high index contrast that you can see in photonic crystal slab, the band is strongly deformed near the band edge that you can see here and a large Δn ranging from 0.1 to 1 can be obtained okay.



Slow Light in Highly Dispersive Structures

- To evaluate v_g of the slow light, the following three methods are used:
  - The frequency-domain interferometric method, which measures the spacing of the Fabry–Pérot resonances or Mach–Zehnder interference (MZI) peaks.
  - The time-domain modulation phase-shift method, which detects the phase of light sinusoidally modulated at gigahertz frequencies.
  - Time-domain direct observation of the short optical pulse transmission.
- A rapid increase in n_g from less than ten to several tens or several hundreds is observed near the band edge using the first two methods, as shown in Figure.

Figure: Transmission spectrum, group-index spectrum and band diagram with respect to the normalized frequency for a silicon PCW. For the group-index spectrum and band diagram, dots denote experimental results obtained by the modulation phase-shift method, whereas dotted lines denote calculated results with an effective-index approximation.

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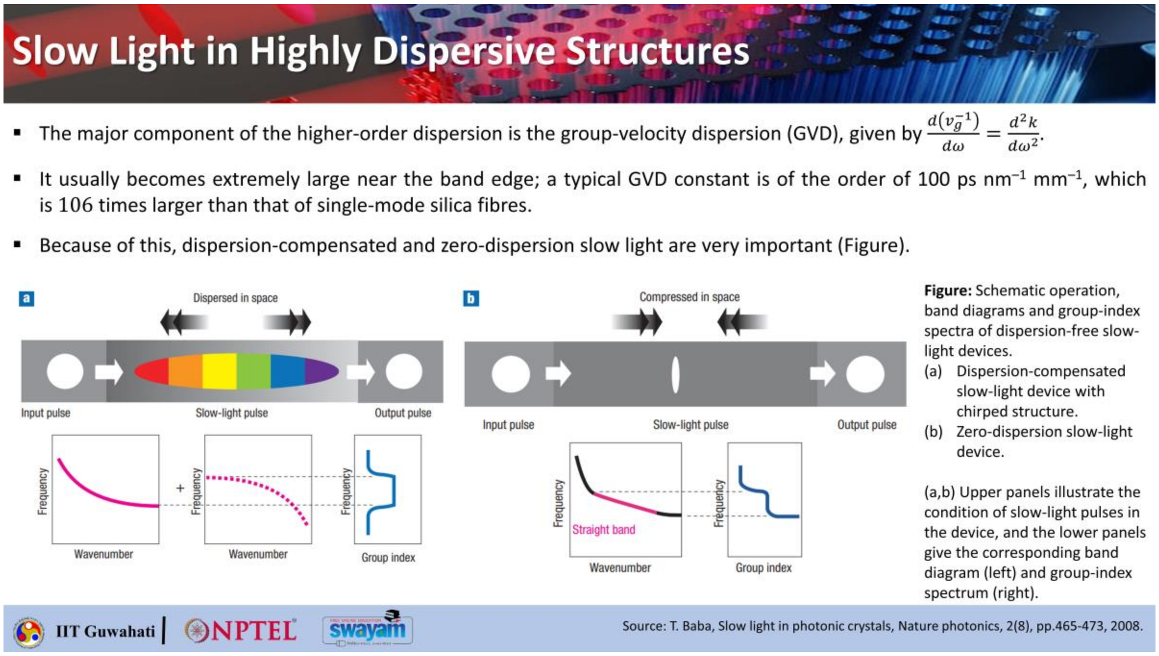
Source: T. Baba, Slow light in photonic crystals, Nature photonics, 2(8), pp.465-473, 2008.

So, to evaluate the v_g that is the group velocity of slow light the following three methods are used. First one is the frequency domain interferometric method which basically measures the spacing of the Fabry-Perot resonances or the Mach-Zehnder interferometer peaks. Second method is the time domain modulation phase shift method which detects the phase of the light that is sinusoidally modulated at gigahertz frequencies. And the third method is time domain direct observation of the short optical pulse transmission, okay. So, a rapid increase in group velocity sorry n_g, group index from less than 10 to several tens or several hundreds is observed near the band edge using the first two methods as you can see in the figure.

So, this shows the transmission, this is the group index and this is the band edge and you can also see the group index severely, seriously increases. So, the transmission spectrum, group index spectrum and the band diagram. So, this is the band diagram with respect to the normalized frequency for silicon photonic crystal waveguide is shown here. For the group index and the band diagram you can see that this particular dots they basically give you the experimental results which are obtained from modulation phase shift method Whereas, the dotted ones are basically the calculation done by effective index approximation.

So, for the simple photonic crystal waveguide, the third method is not easily applied because of severe higher order dispersion.

Scanning near field optical microscopy has revealed pulse programming by capturing snapshots of propagating pulse. where the slow light part has been left behind by the first light parts. So, that way you can see, but it is more or less difficult.



Slow Light in Highly Dispersive Structures

- The major component of the higher-order dispersion is the group-velocity dispersion (GVD), given by $\frac{d(v_g^{-1})}{d\omega} = \frac{d^2k}{d\omega^2}$.
- It usually becomes extremely large near the band edge; a typical GVD constant is of the order of 100 ps nm^{-1} mm^{-1}, which is 106 times larger than that of single-mode silica fibres.
- Because of this, dispersion-compensated and zero-dispersion slow light are very important (Figure).

Figure: Schematic operation, band diagrams and group-index spectra of dispersion-free slow-light devices.
(a) Dispersion-compensated slow-light device with chirped structure.
(b) Zero-dispersion slow-light device.

(a,b) Upper panels illustrate the condition of slow-light pulses in the device, and the lower panels give the corresponding band diagram (left) and group-index spectrum (right).

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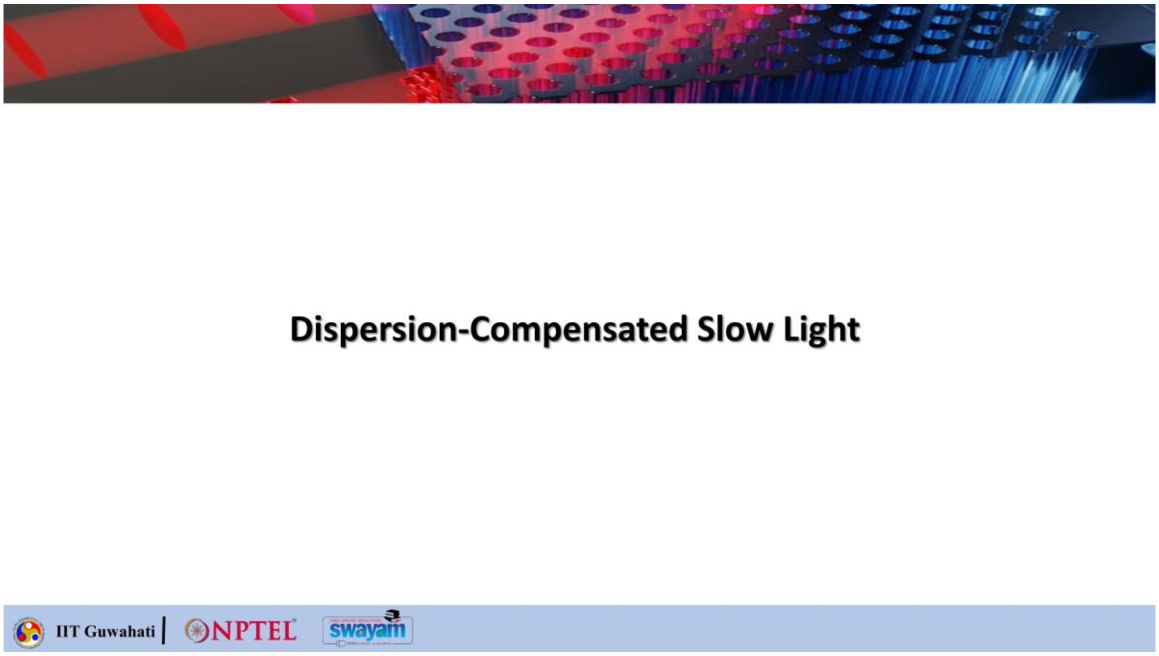
Source: T. Baba, Slow light in photonic crystals, Nature photonics, 2(8), pp.465-473, 2008.

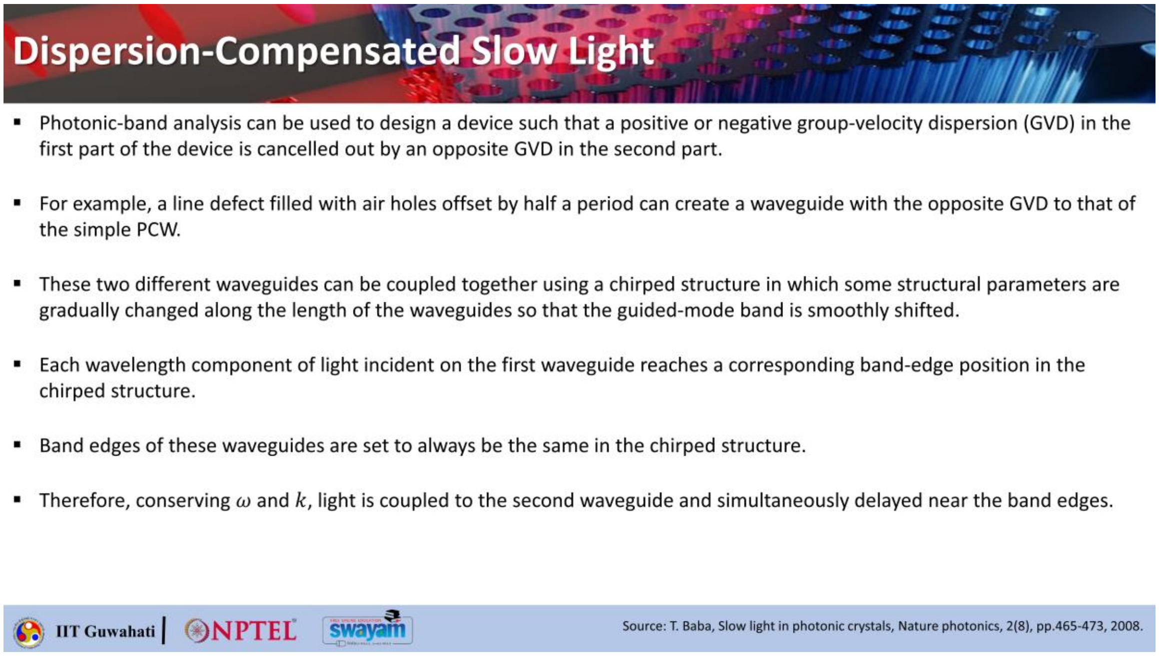
The major component of the higher order dispersion in the group velocity dispersion that is GBD is given by $\frac{d(v_g^{-1})}{d\omega} = \frac{d^2k}{d\omega^2}$.

So, you can get $\frac{d^2k}{d\omega^2}$. So, and it usually becomes extremely large near the band edge and a typical group velocity dispersion constant is of the order of 100 picosecond per nanometer per millimeter, which is typically 100 times or like 106 times larger than that of the single mode silica fibers. because of this you know dispersion compensated and zero dispersion slow light are very important right. So, here you can see in figure A the schematic operation the band diagram and the group index spectra for dispersion free slow light devices are plotted. So, this one is basically for dispersion compensated slow light device with a chirped So, you can see the refractive index is basically varying, darker is higher refractive index, lighter is lower refractive index and you can also see the pulse is getting stretched that way and this is basically a same thing for a zero dispersion slow light device right.

So, with this you can understand even though a high buffering capacity is potentially expected from a large delay bandwidth product in a photonic crystal waveguide device specifically designed for wide band slow light, the net capacity is finally determined by how the GVD is basically getting suppressed.



Dispersion-Compensated Slow Light



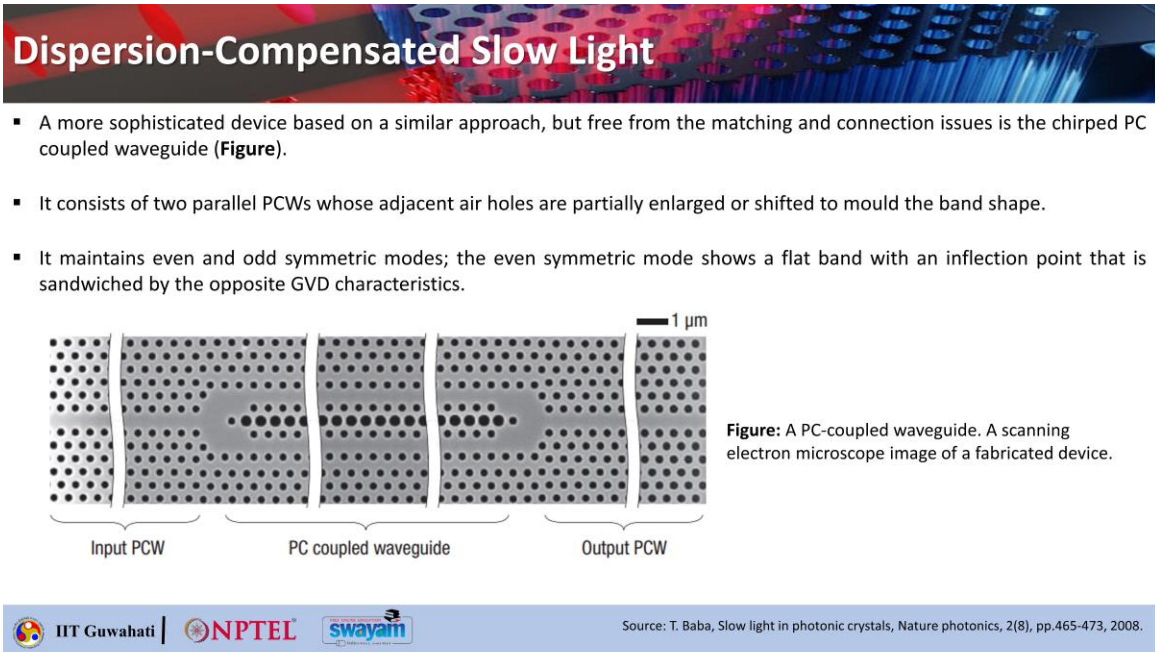
Dispersion-Compensated Slow Light

- Photonic-band analysis can be used to design a device such that a positive or negative group-velocity dispersion (GVD) in the first part of the device is cancelled out by an opposite GVD in the second part.
- For example, a line defect filled with air holes offset by half a period can create a waveguide with the opposite GVD to that of the simple PCW.
- These two different waveguides can be coupled together using a chirped structure in which some structural parameters are gradually changed along the length of the waveguides so that the guided-mode band is smoothly shifted.
- Each wavelength component of light incident on the first waveguide reaches a corresponding band-edge position in the chirped structure.
- Band edges of these waveguides are set to always be the same in the chirped structure.
- Therefore, conserving ω and k, light is coupled to the second waveguide and simultaneously delayed near the band edges.

Source: T. Baba, Slow light in photonic crystals, Nature photonics, 2(8), pp.465-473, 2008.

So, GVD is playing a very important role the group velocity dispersion. So, now let us focus on the dispersion compensated slow light. Photonic band structure analysis can be used to design a device such that a positive or negative group velocity dispersion GVD in the first part of the device is cancelled out by the opposite GVD in the second part, okay. So, with this philosophy you can actually make a zero dispersion, zero dispersion device, right. A line defect filled with air holes offset by half a period can create a waveguide with the opposite GVD to that of the simple PCW.

We will take that example in the coming slides. So, here in this case there are two different types of waveguides which can be coupled together using a chirped structure in which some structural parameters are basically gradually changed along the length of the waveguide so that the guided mode band is smoothly shifted. So, each wavelength component of light incident on the first waveguide could reach a corresponding band edge position in the chirped structure and the band edges of these waveguides are set to always be the same in the chirped structure. Therefore, by conserving the frequency and wave factor or wave number ω and k you can see light is coupled to the second waveguide and simultaneously delayed near the band edge.



Dispersion-Compensated Slow Light

- A more sophisticated device based on a similar approach, but free from the matching and connection issues is the chirped PC coupled waveguide (**Figure**).
- It consists of two parallel PCWs whose adjacent air holes are partially enlarged or shifted to mould the band shape.
- It maintains even and odd symmetric modes; the even symmetric mode shows a flat band with an inflection point that is sandwiched by the opposite GVD characteristics.

Figure: A PC-coupled waveguide. A scanning electron microscope image of a fabricated device.

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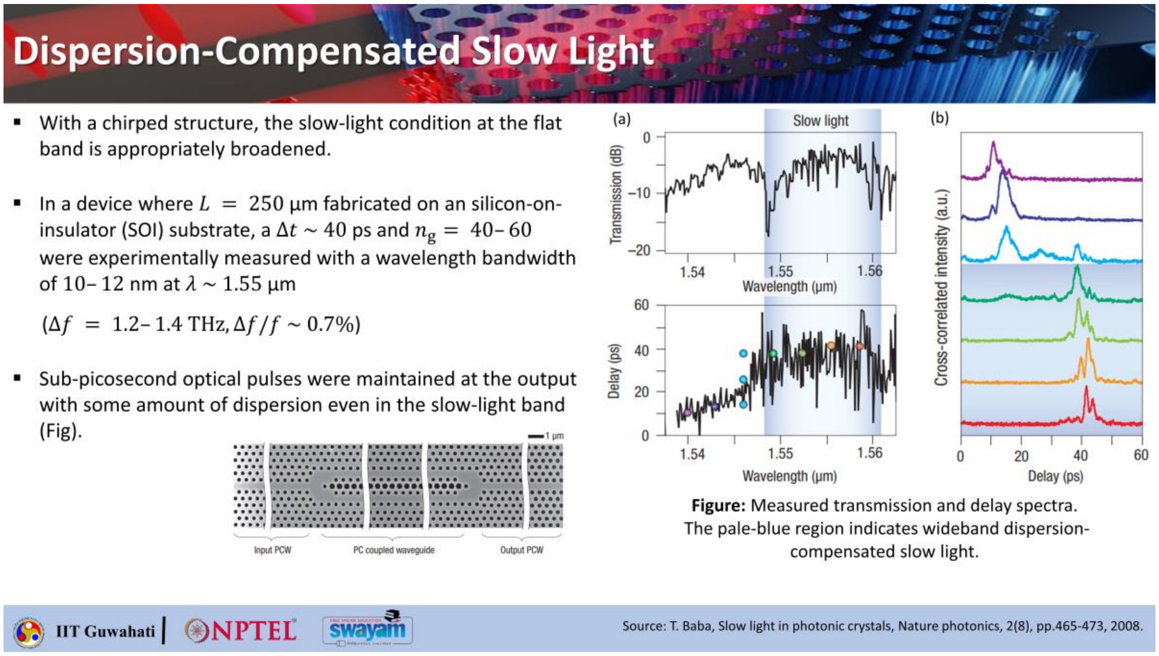
Source: T. Baba, Slow light in photonic crystals, Nature photonics, 2(8), pp.465-473, 2008.

So, finally, the light propagates along and exits the second waveguide. Hence, GVD of slow light is well suppressed over a wide bandwidth that is determined by the chirped range ok.

that that completely eliminated at the central frequency. A more sophisticated device based on a similar approach, but free from matching and connection issues in the chip photonic crystal coupled waveguide is shown here. okay. So, it basically consists of two parallel. So, you can see this is the input PCW, output PCW and here you have two parallel PCWs whose adjacent air holes are partially enlarged and shifted to mould the band shape.

So, it maintains even and odd symmetric modes. The even symmetric modes shows a flat band with an inflection point that is sandwiched by the opposite GVD characteristics.



Dispersion-Compensated Slow Light

- With a chirped structure, the slow-light condition at the flat band is appropriately broadened.
- In a device where $L = 250$ μm fabricated on an silicon-on-insulator (SOI) substrate, a $\Delta t \sim 40$ ps and $n_g = 40\text{–}60$ were experimentally measured with a wavelength bandwidth of 10– 12 nm at $\lambda \sim 1.55$ μm

  ($\Delta f = 1.2\text{–}1.4$ THz, $\Delta f/f \sim 0.7\%$)
- Sub-picosecond optical pulses were maintained at the output with some amount of dispersion even in the slow-light band (Fig).

Figure: Measured transmission and delay spectra. The pale-blue region indicates wideband dispersion-compensated slow light.

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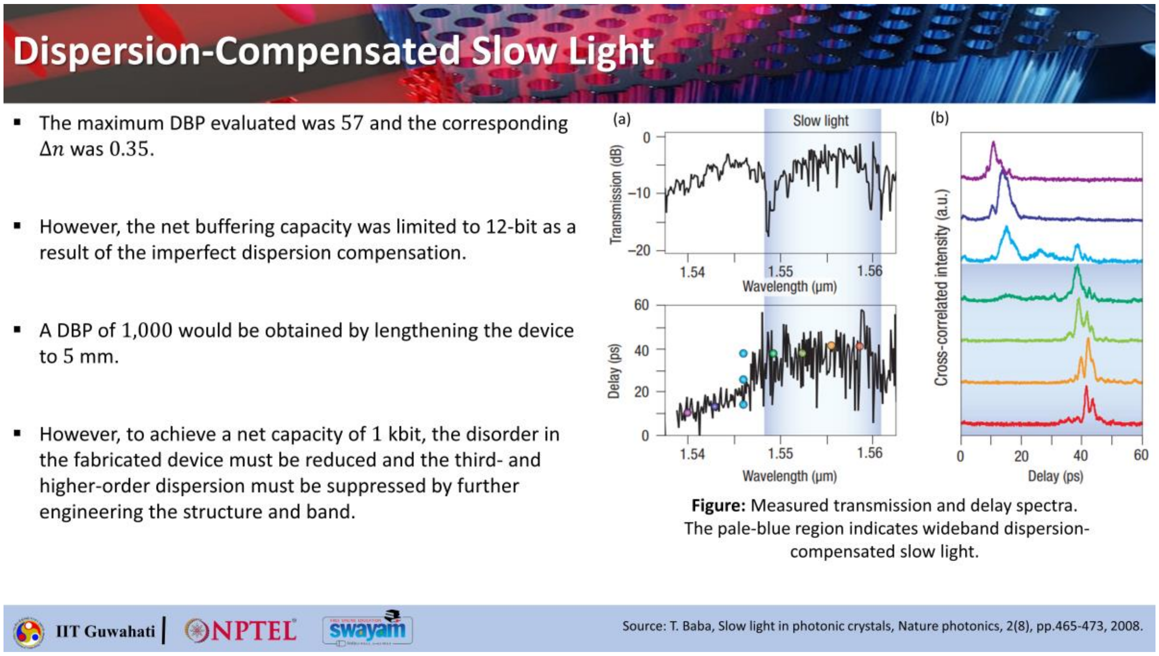
Source: T. Baba, Slow light in photonic crystals, Nature photonics, 2(8), pp.465-473, 2008.

With the chirped structure the slow light condition at the flat band is approximately broadened. So, in a device where L equals you know 250 micron that is basically the length of the device fabricated on a silicon on insulator SOI platform. A Δt that is a delay of 40 picosecond group index of the order of 40 to 60 could be experimentally measured with a wavelength bandwidth of 10 to 12 nanometer at you know the telecom wavelength.

So, your Δf is basically 1.2 to 1.4 terahertz and you can see the fractional bandwidth that is Δf/f equals typically 0.7 percent okay. So, what you see here this basically shows you the measured transmission and delay spectrum. So, the pale blue region this one marks the you know wide band dispersion compensated slow light. The fine oscillations is caused by the internal resonance and the plotted circles correspond to the this circles correspond to the pulse delay that is observed in figure B okay.

So, you can see here this is the delay that has been plotted at all these different wavelengths okay. this tells you the cross correlation trace of optical pulse at each central wavelength which is basically denoted that color of this graph is denoted by this circles that is plotted here okay. So, what you see that sub picosecond ah optical pulses are maintained at the output with some amount of dispersion even in the case of slow light band ok. The maximum delay bandwidth product evaluated was 57 and the corresponding delta n was 0.35.



Dispersion-Compensated Slow Light

- The maximum DBP evaluated was 57 and the corresponding Δn was 0.35.
- However, the net buffering capacity was limited to 12-bit as a result of the imperfect dispersion compensation.
- A DBP of 1,000 would be obtained by lengthening the device to 5 mm.
- However, to achieve a net capacity of 1 kbit, the disorder in the fabricated device must be reduced and the third- and higher-order dispersion must be suppressed by further engineering the structure and band.

Figure: Measured transmission and delay spectra. The pale-blue region indicates wideband dispersion-compensated slow light.

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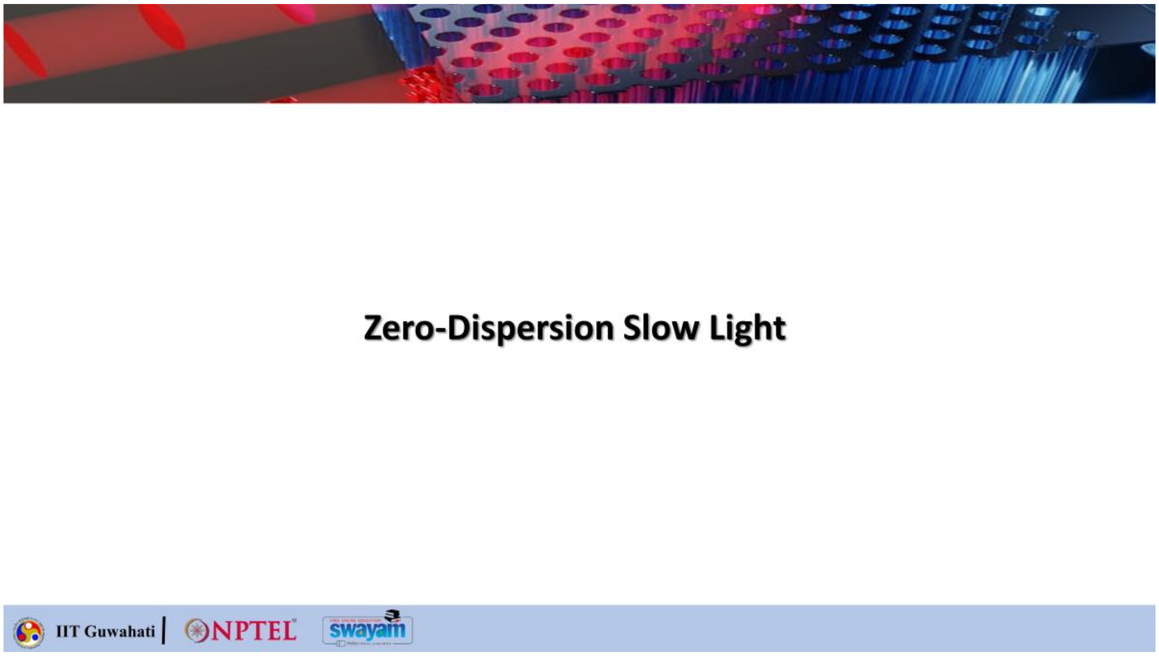
Source: T. Baba, Slow light in photonic crystals, Nature photonics, 2(8), pp.465-473, 2008.

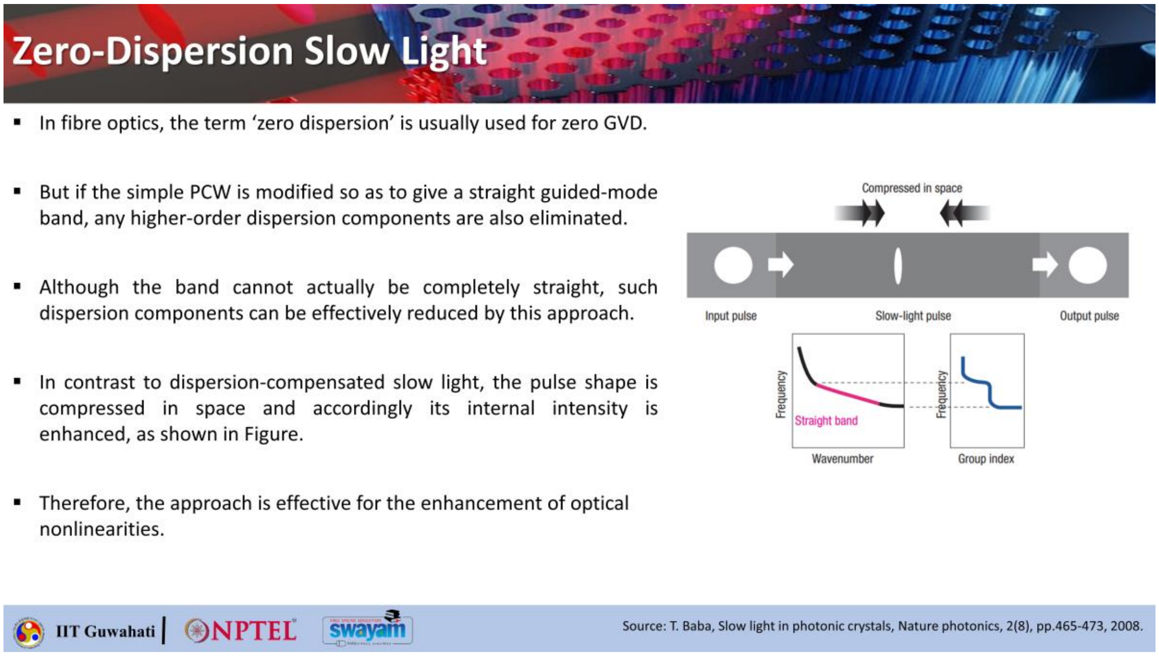
However, the net buffering capacity was limited to 12 bit as a result of imperfect dispersion compensation. A delay bandwidth product of around 1000 could be obtained by lengthening the device. So, if you can make the device length to 5 millimeter you can get a DVP of 1000. However, to achieve a net capacity of 1 kilobit the disorder in the fabricated device must be reduced and the third and the higher order dispersion must be suppressed by further engineering the structure and the band.

So, in these devices the incident optical pulses are basically they are initially specially dispersed and then recovered in the group velocity dispersion compensation process.

Therefore, it is effective for suppressing optical nonlinearity caused by the high intensity of the slow light.



Zero-Dispersion Slow Light



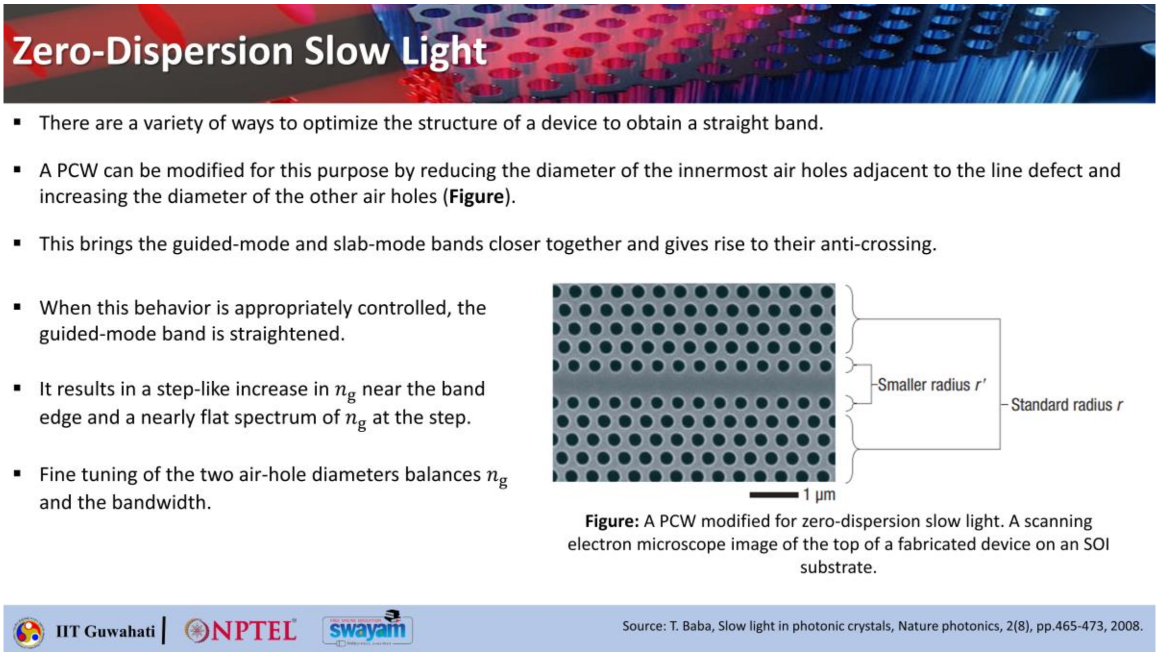
Zero-Dispersion Slow Light

- In fibre optics, the term ‘zero dispersion’ is usually used for zero GVD.
- But if the simple PCW is modified so as to give a straight guided-mode band, any higher-order dispersion components are also eliminated.
- Although the band cannot actually be completely straight, such dispersion components can be effectively reduced by this approach.
- In contrast to dispersion-compensated slow light, the pulse shape is compressed in space and accordingly its internal intensity is enhanced, as shown in Figure.
- Therefore, the approach is effective for the enhancement of optical nonlinearities.

Source: T. Baba, Slow light in photonic crystals, Nature photonics, 2(8), pp.465-473, 2008.

Now we look into zero dispersion slow light how we can achieve that. So, in fiber optics the term zero dispersion is usually used for zero group velocity dispersion GVD right. But if the simple photonic crystal waveguide is modified so as to give a straight guided mode band any higher order dispersion components can be eliminated. Although the band cannot actually be completely straight, such dispersion components can be effectively reduced by this particular approach.

In contrast to dispersion compensated slow light, the pulse shape is also compressed in space and accordingly its internal intensity is enhanced as you can see in this particular figure. So, it shows compression in space okay. So, this is input pulse, this is output pulse and this is slow light pulse which is basically compressed in space. So, this is the corresponding plot of frequency versus wave number and this is the group velocity versus frequency okay. Therefore, the approach is effective for enhancement of optical non-linearities.



Zero-Dispersion Slow Light

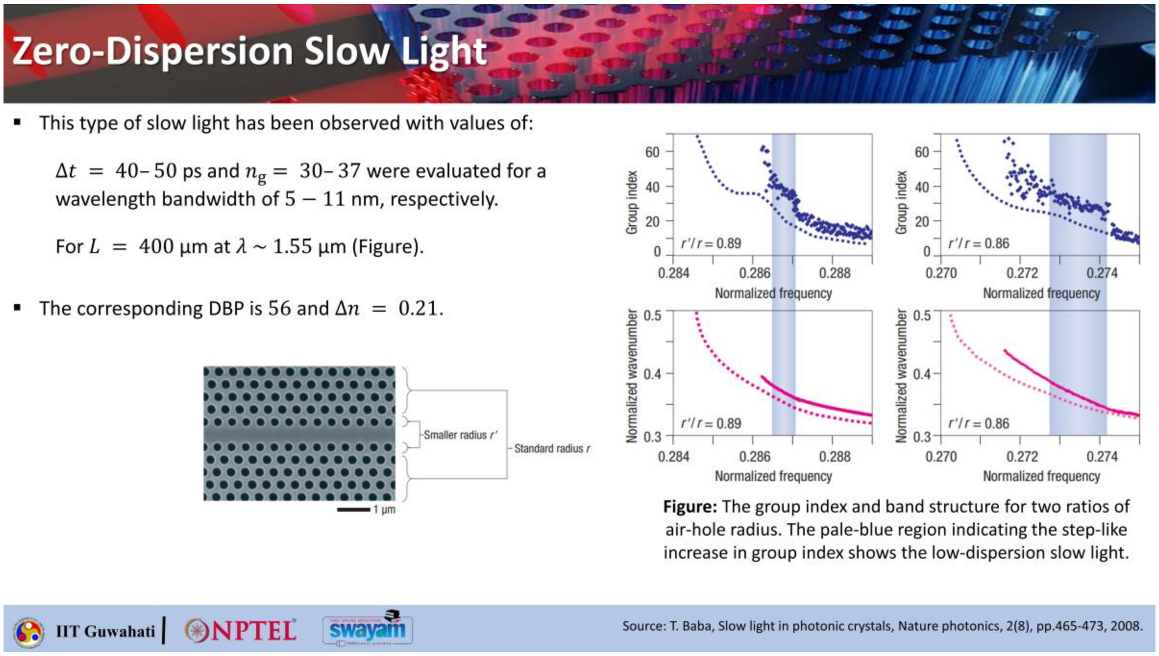
- There are a variety of ways to optimize the structure of a device to obtain a straight band.
- A PCW can be modified for this purpose by reducing the diameter of the innermost air holes adjacent to the line defect and increasing the diameter of the other air holes (**Figure**).
- This brings the guided-mode and slab-mode bands closer together and gives rise to their anti-crossing.
- When this behavior is appropriately controlled, the guided-mode band is straightened.
- It results in a step-like increase in n_g near the band edge and a nearly flat spectrum of n_g at the step.
- Fine tuning of the two air-hole diameters balances n_g and the bandwidth.

Figure: A PCW modified for zero-dispersion slow light. A scanning electron microscope image of the top of a fabricated device on an SOI substrate.

Source: T. Baba, Slow light in photonic crystals, Nature photonics, 2(8), pp.465-473, 2008.

So, if you can compress you can you know excite more non-linear effects. There are a variety of ways to optimize the structure of a device to obtain a straight band. So a PCW can be modified for this purpose by reducing the diameter of the innermost air holes that you can see here. So this is the defect. So you can reduce the diameter of the innermost air holes adjacent to the line defect. And then you can increase the diameter of the other air holes, as you can see here.

So, this is the line defect. So, adjacent you can make this air holes smaller in radius which is marked here with r bar or r' and then these are basically the standard ones or comparatively larger than this ones. So, this brings the guided mode and the slab mode bands together and they give rise to their anticrossing. And while this behavior is appropriately controlled, the guided mode band is basically straightened. So, it is not a very trivial task, it requires a bit of you know tailoring of these diameters to find out which case you will be able to get the guided band straighten up. it results in a step like increase in n_g near the band edge and a nearly flat spectrum of the group index n_g at the step. So, the fine tuning of the two air hole diameters ok, this and this could balance the group index and the bandwidth.



Zero-Dispersion Slow Light

- This type of slow light has been observed with values of:

  $\Delta t = 40\text{–}50$ ps and $n_g = 30\text{–}37$ were evaluated for a wavelength bandwidth of $5 - 11$ nm, respectively.

  For $L = 400$ μm at $\lambda \sim 1.55$ μm (Figure).

- The corresponding DBP is 56 and $\Delta n = 0.21$.

Figure: The group index and band structure for two ratios of air-hole radius. The pale-blue region indicating the step-like increase in group index shows the low-dispersion slow light.

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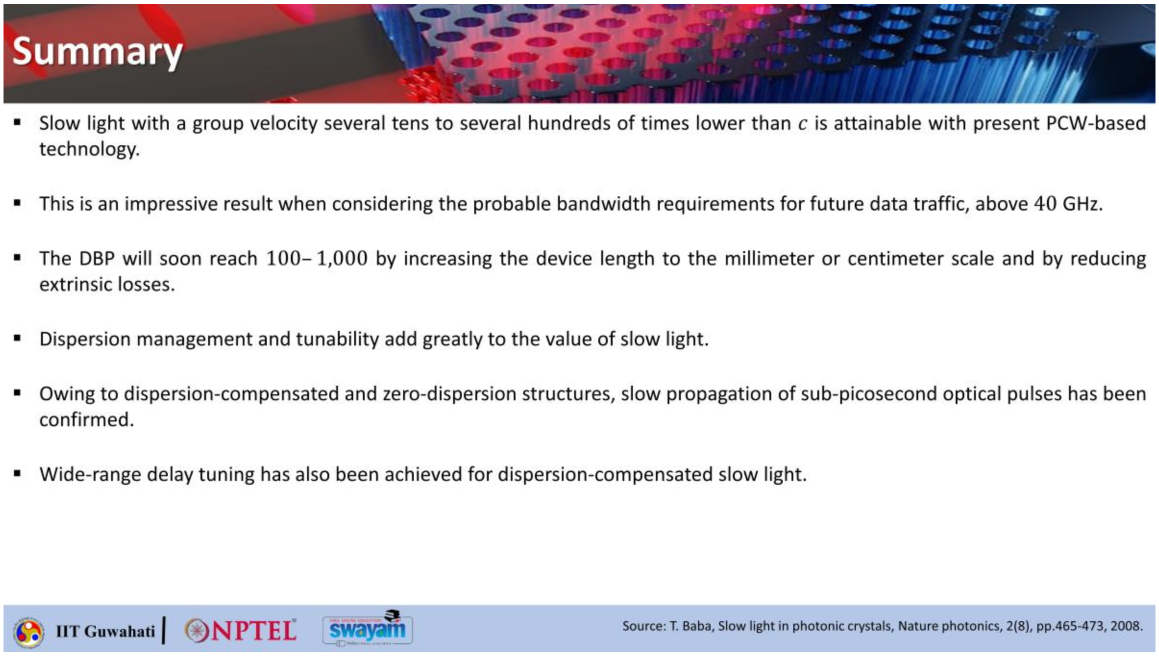
Source: T. Baba, Slow light in photonic crystals, Nature photonics, 2(8), pp.465-473, 2008.

So, this type of slow light has been observed with values of Δt of the order of 40 picosecond and group index to be between 30 and 37 are evaluated for wavelength bandwidth of 5 to 10 nanometer respectively. And this is considered for L equals 400 micrometer at 1550 nanometer wavelength ok. So, here the graph shows the group index ok and the bank structure for the two ratios of air holes.

So, here r' by r is 0.89. So, this is how it changes and here r bar r' by r is basically 0.86 for these two cases. So, once again r' is basically the smaller radius and r is the standard radius. And what is this pale blue region? It indicates the step like increase in group index ok that you see here ok and it shows the low dispersion slow light. The transmission of sub picosecond optical pulses was also observed in this cases as evidence of the low higher order dispersion.

So, here the group index n_g is calculated using modulation phase shift method, where the shift of phase phi between the input and the output ends. okay if you remember the structure okay. So input and output ends of the waveguide is measured for sinusoidally modulated light which has a frequency of omega m and from that you can find out what is the phase and using the modulation phase shift method you can find out what is the group index and that is basically plotted here. And in this case the corresponding Delay bandwidth product comes as to be 56 and Δn is 0.21.



Summary

- Slow light with a group velocity several tens to several hundreds of times lower than c is attainable with present PCW-based technology.
- This is an impressive result when considering the probable bandwidth requirements for future data traffic, above 40 GHz.
- The DBP will soon reach 100– 1,000 by increasing the device length to the millimeter or centimeter scale and by reducing extrinsic losses.
- Dispersion management and tunability add greatly to the value of slow light.
- Owing to dispersion-compensated and zero-dispersion structures, slow propagation of sub-picosecond optical pulses has been confirmed.
- Wide-range delay tuning has also been achieved for dispersion-compensated slow light.

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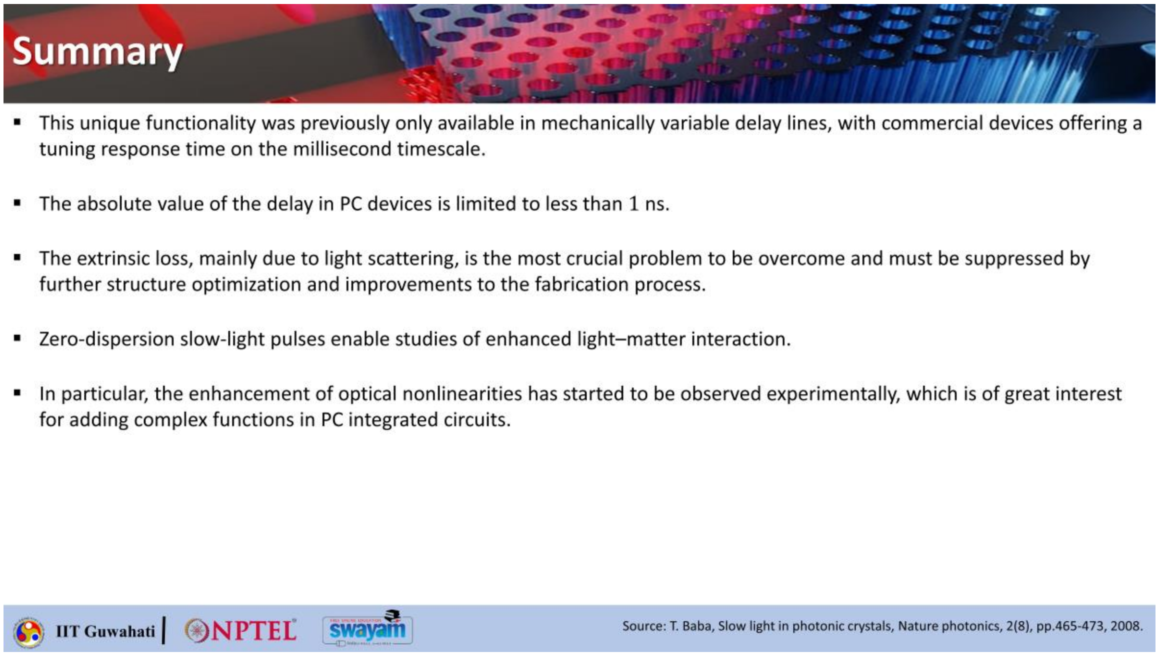
Source: T. Baba, Slow light in photonic crystals, Nature photonics, 2(8), pp.465-473, 2008.

So, what we understood that slow light with a group velocity several tens or several hundreds of times lower than the speed of light in vacuum c is basically attainable with the present photonic crystal waveguide based technology. And this is an impressive result when considering the probable bandwidth requirement for the future data traffic which is above 40 gigahertz. The delay bandwidth product will soon reach to 100 or you know 100 to 1000 by increasing the device length to millimeter or centimeter scale and by reducing the extrinsic losses. Dispersion management and tunability will add greatly to the value of slow light. Going to dispersion compensated and zero dispersion structure, slow propagation of sub picosecond optical pulses have been confirmed.

So, that is a big achievement sub picosecond scale. So, wide range delay tuning has also been achieved for dispersion compensated slow lights. This unique functionality was previously only available for mechanically variable delay lines ok with commercial devices offering you know tuning response time of the order of millisecond time scale ok. So, now with you know the absolute value of delay in photonic crystal devices is limited to less than 1 nanosecond. So, you can understand the improvement that can be achieved using this kind of slow light devices in photonic crystal waveguides.



Summary

- This unique functionality was previously only available in mechanically variable delay lines, with commercial devices offering a tuning response time on the millisecond timescale.
- The absolute value of the delay in PC devices is limited to less than 1 ns.
- The extrinsic loss, mainly due to light scattering, is the most crucial problem to be overcome and must be suppressed by further structure optimization and improvements to the fabrication process.
- Zero-dispersion slow-light pulses enable studies of enhanced light–matter interaction.
- In particular, the enhancement of optical nonlinearities has started to be observed experimentally, which is of great interest for adding complex functions in PC integrated circuits.

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Source: T. Baba, Slow light in photonic crystals, Nature photonics, 2(8), pp.465-473, 2008.

The extrinsic loss mainly due to light scattering is the most critical problem. to overcome and must be suppressed by further structure optimization and improvements in the fabrication process of this web guides. Zero dispersion slow light pulses could enable the study of enhanced light matter interaction and in particular the enhancement of optical non-linearities has started to be observed experimentally which is basically of great interest for adding complex functions to photonic ah crystal integrated circuits. So, with that we will conclude this lecture. And we will start discussion about you know next generation devices such as multiplexers, mode splitters and lasers using photonic crystal in the next lecture will which will be the final lecture of this course.

And in case you have got any queries on this particular lecture you can drop an email mentioning MOOC, photonic crystal and the lecture number on the subject line to this particular email address. Thank you. Thank you.