Fundamentals of structural and material slow and fast light

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Abstract: An overview of fundamentals and methods leading to light velocity control and its applications is provided. These methods allow one to create situations in which the group velocity of light is much smaller than the velocity of light in vacuum *c*, in which the group velocity is greater than *c*, or in which the group velocity is negative. In a nutshell, various quantum interactions between light and matter lead to both high dispersion and transparency in some media. When this is achieved, light pulses passing through the medium can thus be slowed down dramatically, without being absorbed. We present a survey of methods for establishing extreme values of the group velocity, concentrating especially on methods that work in room-temperature solids. Some applications of slow light in telecommunications and computing are discussed.
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1 INTRODUCTION

Controlling the velocity of light has fascinated researchers in optics for the past decade or more. Slow and fast light are the names taken to refer to situations in which the group velocity of a light pulse propagating through a material system is very much different from the vacuum speed of light *c*. One speaks of light being "slow" under circumstances in which the group velocity of light v_g is much smaller than the velocity of light in vacuum(*c*).[1,2] Even more quixotically, there are circumstances in which the group velocity can exceed *c*[3-5]; this occurrence is referred to as "fast light." Most counterintuitive is the case in which the group velocity is negative,[6] implying that the peak of a pulse travels in a direction opposite to that of phase velocity and to that of the energy flow; this circumstance is known as "backwards light." A great impetus for much of the recent interest in slow and fast light is the experiment of Hau et al.[1], which showed that light could be slowed down to the "human" scale of 17m/s. The result was obtained in ultra-cold atom clouds with the use of electromagnetically induced transparency (EIT), which induces transparency in a material while allowing it to retain strong linear and nonlinear optical properties[7]. Slow light can also be obtained through the use of the optical response of hot atomic vapors[2]. More recently, extreme values of vg were realized in room-temperature, solid-state materials, which are more suited for many practical applications. Here we review some of the physical mechanisms that can be used to induce slow and fast light effects in room-temperature solids,[8-10] and we describe some of the exotic propagation effects that can thereby be observed. We also survey some applications of slow and fast light within the fields of quantum electronics and photonics.

2 FUNDAMENTALS

The concept of velocity is well defined for a point particle but becomes murky for wave phenomena. The terms slow and fast light conventionally refer to the group velocity of a light wave. The group velocity is the velocity most closely related to the velocity at which the peak of a light pulse moves through an optical material,[11] and is given by the standard result

$$v_g = \frac{c}{n_g} \qquad n_g = n(k,\omega) + \omega\frac{\partial n(k,\omega)}{\partial \omega} \tag{1}$$

Where n is the refractive index and ω is the angular frequency of the carrier wave of the light field. One refers to light as being slow light for $v_g<c$, fast light for $v_g>c$,[15] and backwards light for v_g negative. Extreme values of the group velocity (that is, vg appreciably different from c) invariably rely on the dominance of the second contribution to the group index of Equation (1). This contribution of course results from the frequency dependence of the refractive index, and for this reason extreme values of the group velocity are usually associated with the resonant or near-resonant response of material systems. This point is illustrated in figures 1 and 2. The left-hand column of Fig. 1 shows why slow light is expected in the wings of an absorption line and fast light is expected near line center. The right-hand column shows that just the opposite is expected for a gain line. Fig. 2 shows the expected behavior for the case of a hole burned into a gain or loss feature. We treat this situation because just this sort of spectral behavior is observed in many nonlinear optical interactions. We also note that spatial dispersion, that is, the non-locality in space of the medium response, is another mechanism that can lead to slow light, as has been predicted[16]andobserved.[17]Early investigations of extreme propagation effects include those of Basov et al.[18] Fax vog et al.[19]and Chu and Wong.[20] More recent interest in slow light was motivated strongly by the experiment of Hau et al.[4] in which slow light (velocities as small as 17m/s) were observed in an ultra-cold sodium vapor. This report was soon followed by that of Kash et al.[5] who showed that ultra-slow light speeds could also be obtained in a hot atomic vapor of rubidium. This observation dispelled the notion that the use of ultra-cold atoms was essential to ultraslow light propagation. Since the time of these early experiments, there have been many reports[21] of slow- and fast-light phenomena under a variety of circumstances.

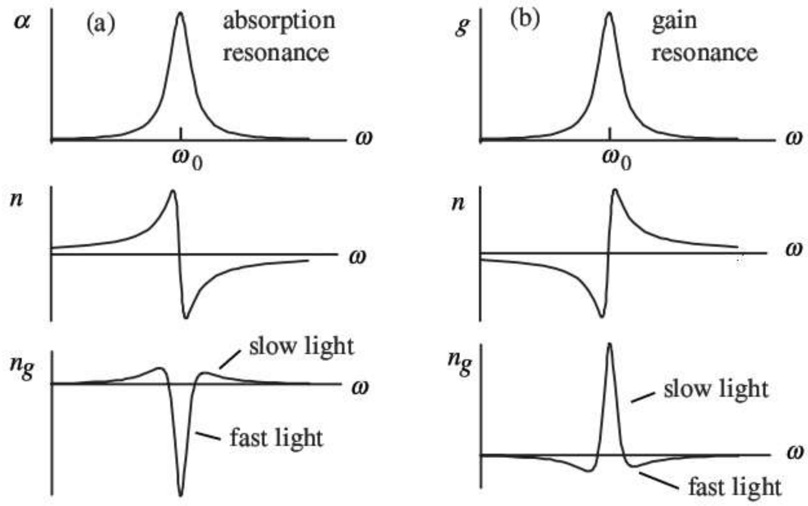


Fig. 1 Origin of slow and fast light for an isolated absorption resonance (a) and gain resonance (b).

3 SLOW LIGHT IN ROOM TEMPERATURE SOLIDS

Many applications of slow light require the use of room-temperature solids, rather than crystals at cryogenic temperatures[5], hot atomic vapors[2], or ultra-cold atomic ensembles.[16] Also tunability of velocity is very essential in many applications. Around this, two methods involving room-temperature solids have emerged as being particularly well suited for use in applications of slow light. These methods are reviewed below.

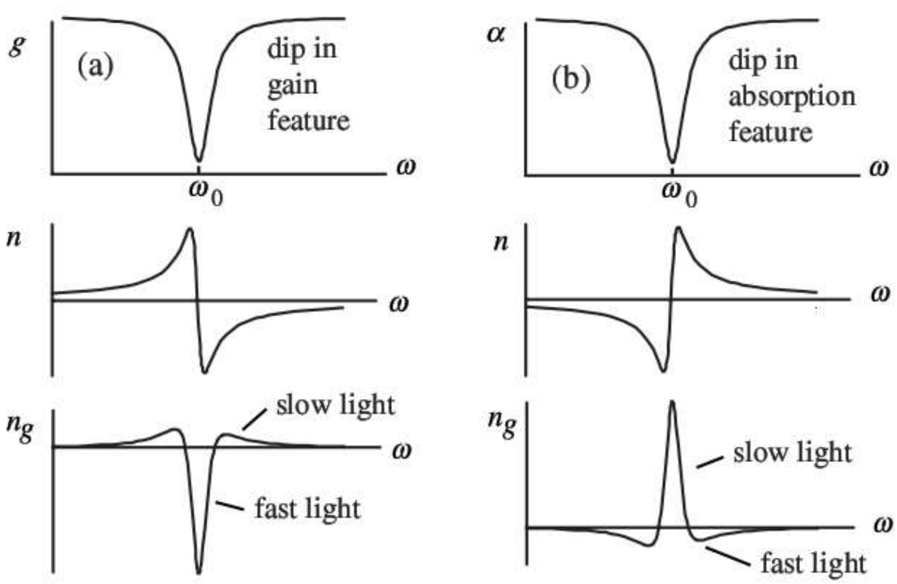


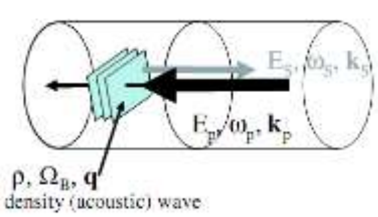
Fig. 2 Origin of slow and fast light for a dip in a gain feature (a) and an absorption feature (b).

Slow light via stimulated Brillouin scattering. Stimulated Brillouin scattering (SBS) is a nonlinear optical process in which an applied laser field scatters from a retreating sound wave to create a down-shifted Stokes wave[22], as illustrated in part (a) of Fig. 3. The sound wave is itself created by the interaction of the laser beam with the Stokes beam through the process of electrostriction. Thus, the stokes beam and the sound wave are mutually reinforcing, leading to the generation of a very strong stokes wave. In fact, ignoring pump depletion, the intensity $I_L$of the Stokes waves grows exponentially, as described by the equations

$$\frac{dI_S}{dz} = -gI_L I_S \quad g = \frac{\gamma_e^2 \omega^2}{nvc^3 \rho_0 \Gamma_B} \quad (2)$$

where γ_e is the electrostrictive constant, v is the velocity of sound, ρ_0 is the mean mass density of the material, Γ_B is the Brillouin linewidth and I_L is the intensity of the pump laser. However, there will necessarily also be a contribution to the refractive index associated with the SBS gain. Furthermore, just as there is gain for a field detuned to the Stokes sideband of the laser field, there will be induced attenuation for a field at the anti-Stokes sideband. Consequently, there will be a region of slow light at the Stokes resonance and aregion of fast light at the anti-Stokes resonance. These features are illustrated in Fig. 3(b).Simple scaling laws show that the induced time delay ΔT for the slow-light situation is of the order of $gI_L L/\Gamma_B$, where L is the length of the interaction region.Slow light based on this process was first observed in optical fibers at a wavelength of 1550 nm by Song et al.[23] and Okawachi et al.[10] A limitation to the usefulness of this process is that the Brillouin linewidth for typical optical fibers is only 30 to 50MHz. This linewidth sets the characteristic frequency bandwidth over which slow-light effects can be observed, and a bandwidth of 30 to 50MHz is much too small for many applications in optical telecommunications. Several procedures have been introduced to broaden this linewidth. One method is to use multiple pump frequencies to produce multiple overlapping gain lines.This idea has been implemented for the case of double[24] and triple[13] gain lines to simultaneously increasethe bandwidth and fractional delay of SBS slow light by factors of the order of two. Another method is tobroaden the linewidth of the laser that pumps the SBS process by adding noise to the current that drives thelaser. This procedure was first implemented by Herra´ezet al.[25] who broadened the intrinsic 35MHzlinewidth of single-mode silica fiber to approximately325MHz. This methods was later extended to achieve a 12GHz bandwidth and to delay 100-ps-longpulses by up to 3 pulse widths.[26]

(a)



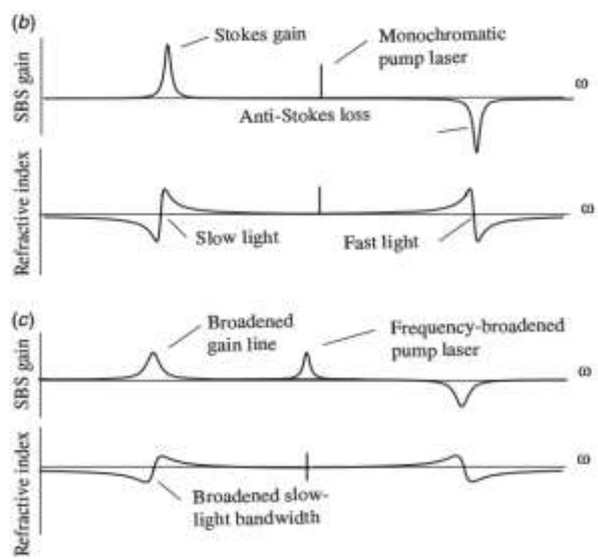


Fig. 3 (a) Schematic representation of the stimulated Brillouin scattering process in an optical fiber. (b) Origin of slow and fast light through SBSand a monochromatic pump field. (c) Origin of slow and fast light through SBS and a broadened pump field.

Slow light via coherent population oscillations. Another method for producing slow light is based on the process of coherent population oscillation(CPO). This process has been studied since the 1960s[27,28]and has successfully been exploited for slow and fast light research.[8,9,11] The idea behind CPO is illustrated in Fig. 4. A strong pump beam which is in resonant with an allowed transition of an assumed structure, and a slightly detuned weak probe beam enter the QD-SOA as the medium for controlling group velocity. If the detuning is smaller than the decay rate of the transition (the inverse of the transition lifetime), the interference of the two beams causes an oscillation of the ground-state population of the saturable absorber at the beat frequency.[29]

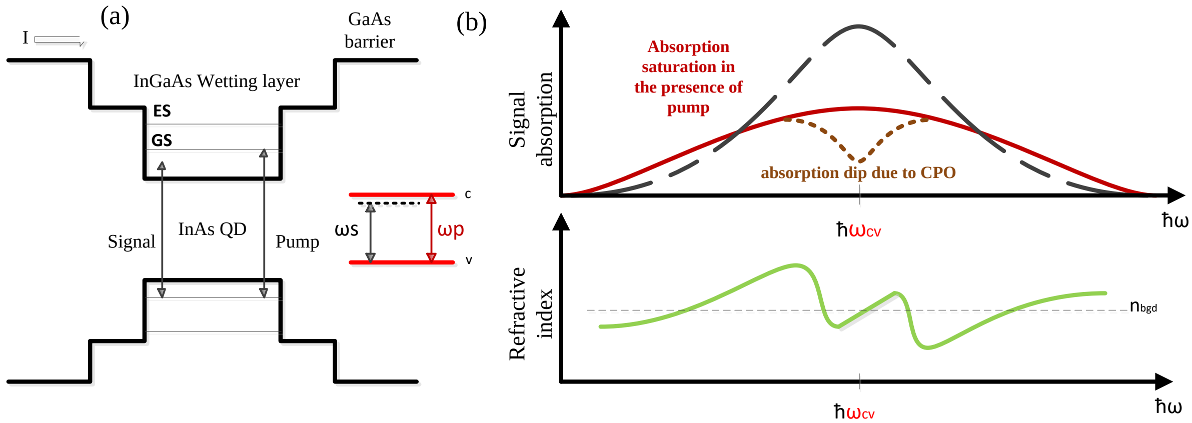


Fig. 4(a) Band diagram in the presence of a resonant pump and a detuned signal (b) Top: absorption spectrum of the signal in the absence (long dashed curve) and the presence (solid) of a strong pump. The spectral hole(dotted curve) is caused by CPO produced by the pump and probe beams. Bottom: the corresponding refractive index spectrum in the presence of CPO.

One may explain this from another point of view; in the presence of an intense optical pump beam with the photon energy near the transition energy of the two-level system, absorption saturation occurs due to depletion of the population in the lower energy state. If a weak signal beam with a frequency slightly detuned from that of the pump beam is present, as shown in Fig. 4(a), the population of the excited state will beat at a frequency determined by the pump-signal detuning. Significant population beating occurs when the population can follow closely the intensity profile due to the time-dependent interference between the optical fields of the pump and signal beams. The coupling between the strong beam and the oscillation of the population results in a reduction of the absorption of the probe beam, as shown in Fig. 4(b), which leads to a rapid index variation around the resonant frequency through the Kramers-Kronig relations. If the frequency of the probe beam fits in the spectral hole, the probe beam will propagate subluminally along the material.
In analysis of CPO based slow light using rate equations coupled with density matrix formalism we can calculate the susceptibility $\chi^{(s)}(\omega_s)$, through the following expression

$$\chi^{(s)}(\omega_s)=\frac{n_d}{\varepsilon_0 h_d}\int_{-\infty}^{+\infty} dEG_E\left[\frac{|M_b|^2.|M_{env}|^2(f_c+f_h-1)}{\hbar\omega_s-E+i\hbar\Gamma_{2,cv}}\right]\times \left[1+2|\Omega_{cv}^{(p)}|^2\times\frac{\left[(\omega_s-\omega_{cv}+i\Gamma_{2,cv})^{-1}-(\omega_p-\omega_{cv}-i\Gamma_{2,cv})^{-1}\right]}{\omega_s-\omega_p+i\Gamma_{1,cv}+2|\Omega_{cv}^{(p)}|^2\left[(2\omega_p-\omega_s-\omega_{cv}-i\Gamma_{2,cv})^{-1}-(\omega_s-\omega_{cv}+i\Gamma_{2,cv})^{-1}\right]}\right] \quad (3)$$

where $|M_b|^2.|M_{env}|^2$ is the momentum matrix element and $|M_{env}|$ is the overlap integral of wave functions ($0<|M_{env}|^2<1$). ε_{bgd}, c, h_d and n_d, are the background permittivity, speed of light in the vacuum, QD height and surface density of QDs per layer. $E(t)$ is the optical field containing different frequency components. The rabi frequency corresponding to the frequency component a is defined as $\Omega_{cv}^{a}=(er_{cv}.E_a)/2\hbar$ .is the angular frequency difference between two states; the subscript *inc* means the incoherent process, and $\Gamma_{2,cv}$ is the dephasing constant.

Then the absorption coefficient $\alpha(\omega_s)$ and corresponding variation of the refractive index $\Delta n(\omega_s)$ can be obtained by the following equations

$$\Delta n(\omega_s) = \mathrm{Re}\left[\sqrt{\varepsilon_{bgd} + \Gamma_{conf}\chi^{(s)}(\omega_s)}\right] - \sqrt{\varepsilon_{bgd}} \quad \alpha(\omega_s) = 2\frac{\omega_s}{c}\mathrm{Im}\left[\sqrt{\varepsilon_{bgd} + \Gamma_{conf}\chi^{(s)}(\omega_s)}\right] \quad (4)$$

where Γ_{conf} is the confinement factor. The group index then can be calculated by

$$n_g = n_{bgd} + \omega_s \frac{\partial \Delta n(\omega_s)}{\partial \omega_s} \quad (5)$$

In practical systems, electrical control of delay/advance is preferable due to the ease of implementation. For this purpose, the SOA bias is varied to investigate its effect on the group index and the resultant delay. If electron-hole pairs are injected into QDs, they saturate the background absorption. Thereupon, the depth of the absorption dip created by CPO is limited and reduced and the corresponding variation of the refractive index is also reduced, as shown in Fig.5(a) and (b). The group index for the probe is varied from 3.4 to more than 16 by tuning the input current source value.

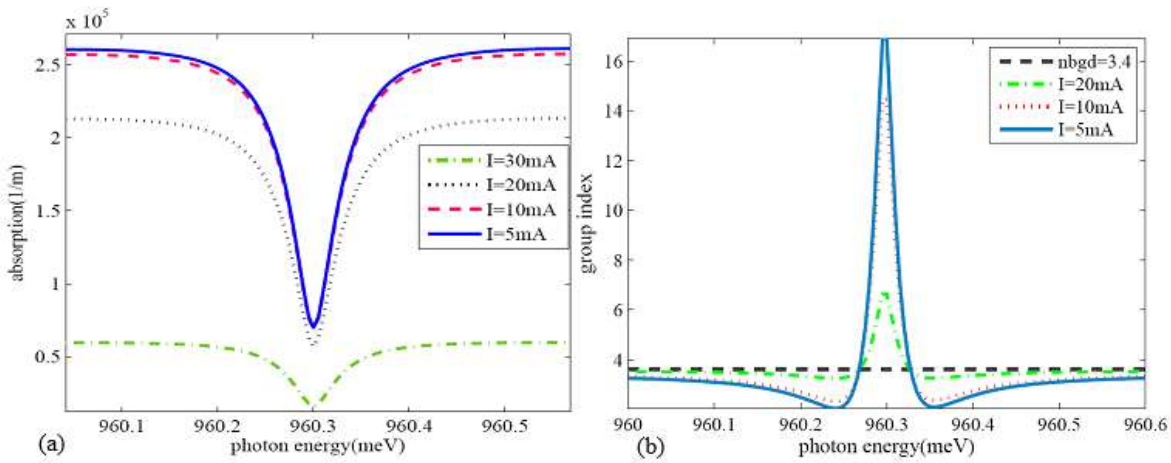


Fig.5 (a) The pump-probe beating creates a coherent spectral hole in the absorption spectrum. (b) Controllable group index.

The CPO effect can also be understood in terms of a time-domain description, as shown in Fig. 6.Here we consider a saturable absorber with non- instantaneous response. We see that the leading edge of the pulse will thus experience more absorption than the trailing edge of the pulse, and that consequently the peak of the pulse will be shifted to later times. It should be mentioned that time domain and frequency domain treatments of CPO are equivalent, with the frequency domain treatment being more convenient for most circumstances.

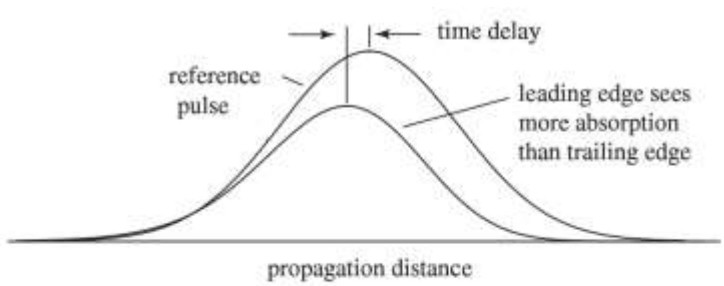


Fig. 6 Time-domain explanation of slow light by means of CPO.

4 SLOW LIGHT IN PHOTONIC CRYSTALS

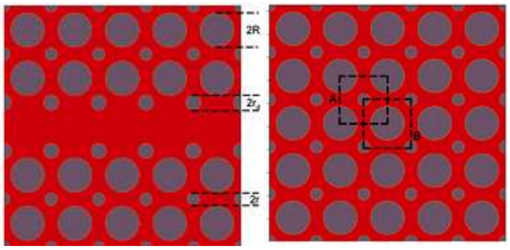
Slow light in photonic crystal waveguide is usually accompanied by the large group velocity dispersion (GVD), which can cause serious distortion of modulated signal in the time domain.[30]Therefore, how to create novel slow light structures having high group index value with small GVD and large bandwidth is an important aspect of photonic crystal research. Very recently, a number of approaches have been proposed to achieve this. For example, modifications of the radius[33] and position[34] in the first one or two row(s) of air holes adjacent to the line defect have been proposed to optimize slow light properties. As shown in Ref. 31-33 authors also recommend introducing the chirped structure into the photonic crystal waveguide to tailor the dispersion properties. But all these structures are based on the monoatomic photonic crystal which has single scatter element in each primitive cell. The alternative photonic crystal geometry can be obtained by increasing the number of different scatter elements in each primitive cell, which can be called polyatomic photonic crystal.[35]The distinctive optical properties of polyatomic photonic crystal stem from the lattice symmetry variation due to the addition of different scatter elements into each primitive cell. Compared with the monoatomic photonic crystal, the polyatomic photonic crystal presents two kinds of advantage. First, the polyatomic photonic crystal leads to the more flexible designs of slow light waveguides. For example, in order to create a waveguide oriented in the ΓX direction in the geometry shown in Fig.7 (a), we can remove one row of big air holes or one row of small air holes. Thus two kinds of slow light waveguides which orient in the same direction can be constructed based on the polyatomic photonic crystals. But, for monoatomic photonic crystal, only one kind of slow light waveguide which orient in the ΓX direction can be constructed. Multiple different scatter elements existing in each primitive cell also provide more freedom to tailor the dispersion relation of the guided modes by subtle structural modification. Second, we can also change the geometric or material characteristics of the scatter elements to modify the lattice symmetry properties of the polyatomic photonic crystal. The impact of lattice symmetry variation on the dispersion relation of the guided modes can be explored to create novel photonic crystal slow light waveguides with small GVD and large bandwidth. So extensive research work is really needed to investigate the slow light phenomenon in the polyatomic photonic crystal. The most important issue for slow light devices is the group index n_g which can be written as in Ref. 36:

$$n_g = c / vg = c\frac{dk}{d\omega} \tag{6}$$

The related n_g curves with normalized frequency under different values of r_d are displayed in Fig. 7(b). All calculated n_g curves are U-shaped and the bottom of this U shape is very appropriate for obtaining constant group index with small GVD and large bandwidth. This figure clearly illustrates the influence of radius r_d on the slow light properties. The modulus of the group index n_g and the corresponding normalized frequency increases with the radius r_d, but the bandwidth decreases when the radius r_d increases. We also calculate the average group index and corresponding bandwidth value with different radius r_d. The average group index can be evaluated by[37]:

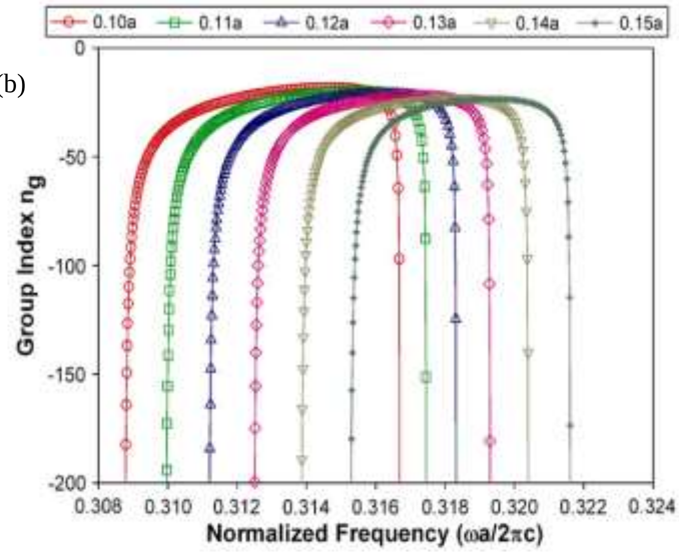
$$n_g = \int_{\omega_0}^{\omega_{0+\Delta\omega}} n_g(\omega)\,\mathrm{d}\,\omega / \Delta\omega \tag{7}$$

Where △ω represents the bandwidth of slow light, which is defined as the wavelength range corresponding to a maximum of 10% n_g.



(a) .7(a)Schematic picture of the diatomic photonic crystal structure, (b)Group index variation versus normalized frequency for different values of r_d.

(b)



5 APPLICATIONS OF SLOW AND FAST LIGHT

All optical communications. Controlling the group velocity of light pulses is useful to achieve various functionalities such as buffering in an all-optical network. Fig.8 shows how a slow-light buffer might be used to increase the throughput of a telecommunication system. Part (a) of the figure shows two data packets arriving simultaneously at an optical switch. If these two data packets are intended for the same output port, a problem occurs because the switch cannot handle the two data packets simultaneously. In the worst case, one of the data packets is simply dropped and must be retransmitted at a later time. This procedure of course simply makes the problem of system overload worse, as certain data packets have to be transmitted more than once. A more desirable resolution is to construct a controllable delay line that can act as a buffer for a complete data packet, as shown in part (b)of the figure. In this scenario, one data packet is directed into the buffer and is released only after the other data packet has cleared the switch. To implement this idea, the delay line needs to be able to store as many bits of information (data pulses) as are contained in a data packet. This number is determined by the system architecture. In most implementations, at least 1024 bits of data would be contained in each data packet. In fundamental terms, the number of stored pulses is known as the delay- bandwidth product of the delay line. There have been a number of analyses of the theoretical limit to how large the delay-bandwidth-product of a slow-light delay line can be.[38-40] The general conclusion of these analyses seems to be that there is no fundamental limit to how large the delay-bandwidth product can be, although there can be serious practical problems involved in obtaining a large value of the delay-bandwidth product. In fact, to date, the largest value of the delay-bandwidth product obtained using true slow light is the value of 80 pulse widths reported by Camacho et al.[41] However, the C/D method has been able to achieve a storage capacity of 440 bit slots, or approximately 880 pulse widths, which is large enough to prove useful in actual communication systems. Another application of slow and fast light is in the area of data pulse regeneration. In an optical communication system, each pulse needs to be centered in its time widow. However, due to environmental effects and optical sources of noise, individual pulses might become displaced from the centers of their time windows. The use of slow- and fast-light methods could provide a useful means for the real-time centering of pulses in their time windows. For both buffering and regeneration, it is crucial that the pulse shape does not become distorted as a result of the slow- or fast-light effect. Various methods have been demonstrated for minimizing pulse-shape distortion.

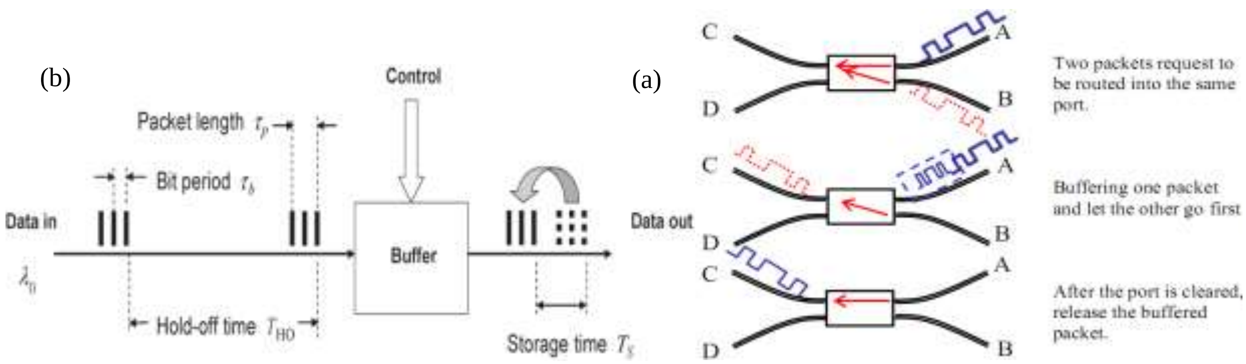


Fig. 8 Slow light optical buffer providing contention resolution in an optical switch.

RF photonics. In the last decades, there has been an increasing interest in exploiting the unique characteristics of photonics technology in the generation, processing, and transport of microwave, millimeter, and terahertz wave signals. Among the various applications of optical processing of microwave signals, the use of optics to control the microwave signal delay is one of the most interesting areas. This technology enables the use of photonic components for two important practical applications: the advanced filtering of signals and the implementation of optically fed phased-array antennas. Photonic components are a very attractive enabling technology for these applications due to their low attenuation, light weight, small size, high flexibility, and broad bandwidth.[42]

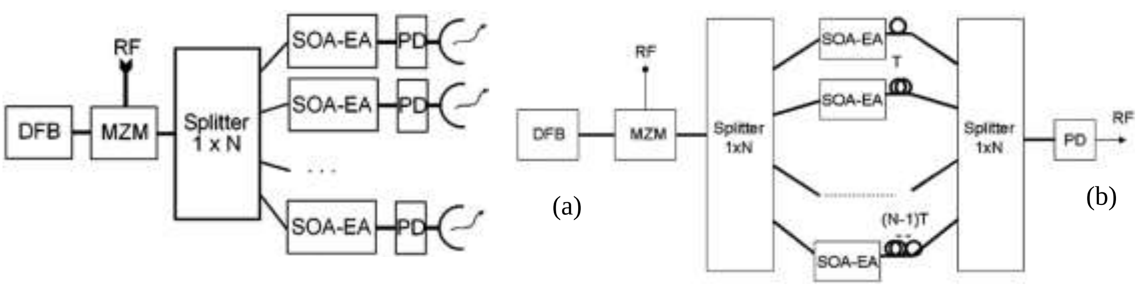


Fig. 9 (a) Schematic diagram of a phased-array antenna using SOA-EA devices as true time delay elements.(b)Layout of a tunable microwave photonic filter using SOA-EA devices to implement complex tap coefficients. DFB: Distributed feedback laser. MZM: Mach–Zehnder modulator.

Part (a) of Fig. 9 illustrates the scheme of an optically fed phased-array antenna where the phase provided to each antenna is controlled by the use of the proposed alternating SOA and EA sections. The phased array is a directive antenna made of individual simple radiating antennas, which generate a radiation pattern whose shape and direction is determined by the relative phases and amplitudes of the currents to the individual elements. In this particular implementation, the radio-frequency (RF) signal is modulated onto an optical carrier and transmitted to photodetectors that are connected to individual antennas. Varying the injection currents of the SOA and EA sections, it is possible to control the phases and amplitudes of the microwave signals. It is necessary to create a matrix of values to obtain the required phase and amplitude values at the same time. Fig. 9(b) shows the layout of a microwave photonic transversal filter. The signal from a continuous-wave optical source is modulated by a microwave signal and then it is split among different taps, each one providing an incremental delay value of seconds over the previous one. In this context, the SOA-EA devices can be employed in each tap to provide an extra controllable microwave phase delay, thus making possible the implementation of filters with complex coefficients. The availability of structures with complex coefficients is crucial to implement tunable filters where the filter free-spectral range is not altered while tuning the resonance to a particular value.

6 SUMMARY

Slow light methods have advanced dramatically in recent years. Many of the fundamental aspect of slow and fast light are currently well understood. Thus, slow light research has turned to the equally exciting task of developing applications of this new technology.

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