# A Review of Slow Light Physics and Its Applications

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**Abstract:** An overview of physical mechanisms leading to small group velocity light, or slow light, is provided. 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. In some cases, pulses can even be stopped completely, and the information they carry temporarily transferred to the medium. Pulses can then be "revived" with their original information intact. Applications of these phenomena in telecommunications and computing are discussed.



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## References and links

1. Leon Brillouin. *Wave Propagation and Group Velocity*. Academic Press, 1960.
2. Lene Vestergaard Hau, S. E. Harris, Zachary Dutton, and Cyrus H. Behroozi. Light speed reduction to 17 metres per second in an ultracold atomic gas. *Nature*, 397:594–598, 1999.
3. Michael M. Kash, Vladimir A. Sautenkov, Alexander S. Zibrov, L. Hollberg, George R. Welch, Mikhail D. Lukin, Yuri Rostovtsev, Edward S. Fry, and Marlan O. Scully. Ultraslow group velocity and enhanced nonlinear optical effects in a coherently driven hot atomic gas. *Physical Review Letters*, 82:5229–5232, 1999.
4. D. Budker, D. F. Kimball, S. M. Rochester, and V. V. Yashchuk. Nonlinear magneto-optics and reduced group velocity of light in atomic vapor with slow ground state relaxation. *Physical Review Letters*, 83:1767–1770, 1999.
5. Matthew S. Bigelow, Nick L. Lepeshkin, and Robert W. Boyd. Observation of ultraslow light propagation in a ruby cristal at room temperature. *Physical Review Letters*, 90(11), 2003.
6. Kwang Yong Song, Miguel González Herráez, and Luc Thévenaz. Observation of pulse delaying and advancement in optical fibers using stimulated Brillouin scattering. *Optics Express*, 13(1):82–88, 2005.
7. Jay Sharping, Yoshitomo Okawachi, and Alexander Gaeta. Wide bandwidth slow light using a Raman fiber amplifier. *Optics Express*, 13(16):6092–6098, 2005.
8. A. Schweinsberg, N.N. Lepeshkin, M.S. Bigelow, R.W. Boyd, and S. Jarabo. Observation of superluminal and slow light propagation in Erbium-doped optical fiber. *Europhysics Letters*, 73(2):218–224, 2005.
9. Miguel González Herráez, Kwang Yong Song, and Luc Thévenaz. Arbitrary-bandwidth Brillouin slow light in optical fibers. *Optics Express*, 14(4):1395–1400, 2006.
10. Chien Liu, Zachary Dutton, Cyrus H. Behroozi, and Lene Vestergaard Hau. Observation of coherent optical information storage in an atomic medium using halted light pulses. *Nature*, 409:490–493, 2001.
11. Ronald Walsworth, Susanne Yelin, and Mikhail Lukin. The story behind "stopped light". *Optics and Photonics News*, 13(5):50–54, 2002.
12. Claude Aslangul. *Applications de la Mécanique Quantique*. Ecole Normale Suprieure, Paris, 2005.
13. Claude Cohen-Tannoudji. Manipulating atoms with photons. *Physica Scripta*, T76:33–40, 1998.
14. Daniel J. Gauthier and Robert W. Boyd. Fast light, slow light and optical precursors: What does it all mean? *Photonics Spectra*, pages 82–90, Jan. 2007.
15. Matthew S. Bigelow, Nick L. Lepeshkin, Heedeuk Shin, and Robert W. Boyd. Propagation of smooth and discontinuous pulses through materials with very large or very small group velocities. *Journal of Physics: Condensed Matter*, pages 3117–3126, Mar. 2006.

16. Claude Cohen-Tannoudji. Linear superposition of states in radiative processes. *Physica Scripta*, T70:79–87, 1997.
17. Stephen E. Harris. Electromagnetically induced transparency. *Physics Today*, 50(7):36–42, 1997.
18. G. Alzetta, A. Gozzini, L. Moi, and G. Orriols. An experimental method for the observation of RF transitions and laser beat resonances in oriented Na vapour. *Il Nuovo Cimento*, 36B(5), 1976.
19. Robert W. Boyd, Daniel J. Gauthier, and Alexander L Gaeta. Applications of slow light in telecommunications. *Optics and Photonics News*, pages 18–23, Apr. 2006.
20. Barbara Goss Levi. Researchers stop, store, and retrieve photons – or at least the information they carry. *Physics Today*, 54(3):17–19, 2001.

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## 1. Introduction

The fact that the group velocity of light pulses is dependent on the dispersion properties of a medium is a well-known consequence of Maxwell's equations. Discussions about the speed of light in dispersive media arose as early as in the 1900s, as it was realized that some media properties could lead to group velocities higher than the speed of light in vacuum ($c \simeq 3 \times 10^8\, m.s^{-1}$). Arnold Sommerfeld and Leon Brillouin were among the first to deeply research the subject (see Ref. [1]), and to convincingly prove that information can never travel faster than $c$.

On the other end of the spectrum, dispersive materials can also lead to very small group velocities. Recent experiments have taken advantage of this fact to slow down light pulses to a fraction of $c$. For instance, Hau *et al.* [2] observed light slow down to $17\, m.s^{-1}$ at ultra low temperature in a Bose-Eistein condensate. Later on, Kash *et al.* [3] slowed light down to $90\, m.s^{-1}$ in rubidium vapor. This experiment was then refined by Budker *et al.* [4], and light was slowed down to $8\, m.s^{-1}$. Finally, Bigelow *et al.* [5] were able to slow light down to less than $58\, m.s^{-1}$ at room temperature in a ruby cristal. Researchers have also shown the potential for slow light in erbium-doped optical fiber (see Ref. [6], [7], [8], and [9]).

The ultimate version of slow light was achieved in recent years when various groups, including Liu *et al.* [10] and Walsworth *et al.* [11], reported stopping light altogether. In those experiments, information carried by light pulses was temporarily stored in the dispersive medium, enabling researchers to subsequently recreate light pulses carrying the same information, with relatively small losses.

In a first part, we will discuss the physics of slow light. The first barrier encountered in the search for slow light is the fact that high dispersion is usually synonymous with high absorption in the medium. Fortunately, techniques based on quantum effects arising from the interaction of light with matter have enabled researchers to couple high dispersion with low absorption, or transparency.

In a second part, we will see how recent experiments have implemented some of these transparency techniques to observe light pulses slowed down to very mundane velocities. We will also discuss how dynamic adaptations of these techniques have been successfully used to stop and store light.

Finally, we will review potential future applications for slow light and stopped light, particularly in the domains of computing and telecommunications. Although the field is still young, many promising applications have already been found. Paradoxically, we will see that slowing down light can lead to faster computing. At the same time, stopping light could potentially lead to new methods to store information.

## 2. The physics of slow light

### *2.1. Group velocity in dispersive media*

In a light pulse, the group velocity, noted $v_g$, is the velocity of the energy, or more prosaically the velocity of photons in the pulse. It is associated with the Poynting vector $\mathbf{S}$, while the phase velocity, noted $v_\phi$ is associated with the wave vector $\mathbf{k}$. In this article, we will focus on group velocity, as it is the only velocity that really matters when one talks about information or energy.

Phase velocity is traditionally defined using of the pulsation-dependent refractive index $n(\omega)$ of a medium, through the relation $v_\phi(\omega) = \dfrac{c}{n(\omega)}$. In the same manner, one can define group velocity as $v_g(\omega) = \dfrac{c}{n_g(\omega)}$, where $n_g(\omega)$ verifies:

$$n_g(\omega) = n(\omega) + \omega \frac{dn}{d\omega}(\omega) \tag{1}$$

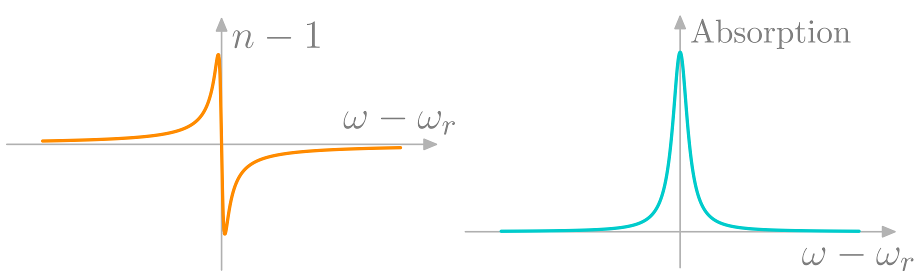
This equation clearly shows the dependency of $v_g$ on the dispersion $\dfrac{dn}{d\omega}$ of the material. It also shows that group velocity can be drastically reduced in materials for which $\dfrac{dn}{d\omega} \gg 1$.

Unfortunately, most of the time, dispersion in materials is small. It only increases significantly near resonances, where absorption becomes a problem. For instance, all media exhibit absorption lines that can be understood qualitatively with the well-known harmonic oscillator model. In this model, atoms are viewed as oscillators, with electrons moving back and forth around the position of the positively-charged nucleus. This model leads to a straightforward expression for the susceptibility of the material (in the case of a single absorption line):

$$\chi(\omega) = \frac{N q_e^2}{\varepsilon_0 m_e} \frac{1}{\omega_r^2 - \omega^2 - i\omega/\tau} \tag{2}$$

where $N$ is the density of dipoles in the medium, $q_e$ is the charge of the electron, $\varepsilon_0$ the permittivity of vacuum, $m_e$ the mass of the electron, $\omega_r$ the resonant pulsation, and $\tau$ the typical relaxation time of the oscillator.

The refractive index of the medium is defined as $n(\omega) = \Re\left(\sqrt{1+\chi(\omega)}\right)$. The absorption coefficient of the medium is defined as $\alpha(\omega) = 2k_0\Im\left(\sqrt{1+\chi(\omega)}\right)$, where $k_0$ is the norm of the wave vector $\mathbf{k}_0$ in vacuum. Fig. 1 shows $(n-1)$ and $\alpha$ with respect to pulsation in the vicinity of the resonance for the harmonic oscillator model with a single resonant pulsation.



(a) Refraction index (b) Absorption

Fig. 1. Refraction index and absorption coefficient for the harmonic oscillator model in the vicinity of a single resonant pulsation.

The problem of high absorption can be solved thanks to electromagnetically induced transparency, or EIT.

### 2.2. *Electromagnetically induced transparency*

If the well-known Kramers-Krönig relations show that an extremum of the absorption coefficient must be reached when the dispersion of a medium is large, nothing prevents this extremum from being a minimum. Electromagnetically induced transparency, or EIT, takes advantage of that fact by coupling a dispersion maximum with an absorption minimum in the medium.

EIT is fundamentally driven by quantum-mechanical processes. The simplest form of EIT is related to the Stark and Zeeman effects (see for instance Ref. [12]). We will give here a brief description of the Stark effect, related to electric fields. The probably better known Zeeman effect is similar, although the electric field is replaced by a magnetic field.

Consider a volume filled with hydrogen atoms. If a DC electric field is applied to the volume, the multiply degenerate $|2\rangle$ state splits into three states with distinct energies. In keeping with the traditional $|n,\ell,m\rangle$ notation, while the $|2,1,\pm1\rangle$ states remain degenerate and keep their original energy $E_2$, the $|2,0,0\rangle$ states mixes with the $|2,1,0\rangle$ states to generate the states $|2\pm\rangle$ with respective energies $E_2 \pm 3\,|q_e|\,\mathscr{E} a_0$, $\mathscr{E}$ being the norm of the applied DC electric field and $a_0$ the Bohr radius.

The new states are:

$$|2+\rangle = \frac{1}{\sqrt{2}}\left(|2,1,0\rangle + |2,0,0\rangle\right)$$
$$|2-\rangle = \frac{1}{\sqrt{2}}\left(|2,1,0\rangle - |2,0,0\rangle\right)$$

If a laser beam is polarized linearly, selection rules dictate that only transitions with $\delta m = 0$ may occur. Hence, if we only take into account the lower two energy states of the hydrogen atom, the only possible transitions when a DC electric field is present are those coupling the ground state $|1\rangle$ with any of the Stark-splitted $|2\pm\rangle$ states.

Hence, we find ourselves in the situation of Fig. 2.

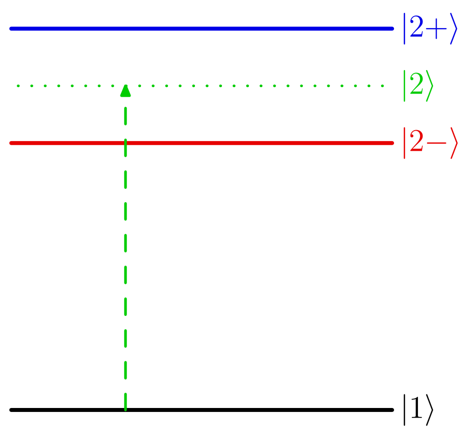
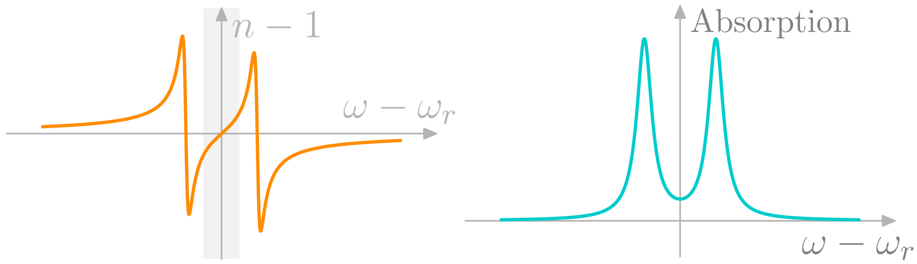



Fig. 2. Stark effect: The splitting of excited state $|2\rangle$ into two distinct states $|2\pm\rangle$ prevents monochromatic light with pulsation corresponding to the original energy difference from being absorbed, or more precisely scattered, by the atoms.

We now have two close resonances for the harmonic oscillator model, and Fig. 3 shows the refractive index and absorption curves in the vicinity of such a double resonance.

It is clear in Fig. 3 that there is a range of pulsations between the resonances that combine high dispersion (a positive slope on the refraction index curve, leading to small group velocities) with low absorption, or high transparency of the medium.



(a) Refraction index (b) Absorption

Fig. 3. Refraction index and absorption coefficient for the harmonic oscillator model in the vicinity of two close resonant pulsations.

Although the Stark effect is a simple example, all mechanisms leading to EIT take advantage of well-known consequences of the interaction between atoms and photons (see Ref. [13]).

### *2.3. Avoiding distortion*

There are other problems limiting the effectiveness of high dispersion techniques. In particular, as noted in Ref. [14], higher-order dispersion, arising from the nonlinear dependence of the refractive index on the impulsion power, must be minimized in order to avoid pulse distortion in the medium. This is achieved by making sure that the pulse duration is long enough to narrow down the spectrum width of the pulse into a region (shown in grey in Fig. 3(a)) where the variation of the refractive index is essentially linear with respect to the pulsation.

Pulse distortion, and how to avoid it, is also discussed in more details in Ref. [15].

## 3. Practical implementations

In this section, we will see how recent experiments have implemented EIT to observe slow light propagation, and how a dynamic form of EIT was used to even stop and momentarily store light in a medium.

### *3.1. Coherent population trapping*

"Coherent population trapping", or CPT (see for instance Ref. [16]) is one of the leading techniques used to induce transparency in a medium. It involves situations where atoms are forced into a linear superposition of states. Zeeman or Stark-splitted states are good candidates, but Harris [17] also describes how any two states that are separated by a Raman (non allowed) transition work in the same way. In the latter case, a coupling laser $L_c$ and a probing laser $L_p$ are involved, as shown in Fig. 4. The frequency difference between the lasers is chosen to be equal to the frequency of a Raman transition of a medium. The process was discovered by Alzetta *et al.* in 1976 [18]. It is also possible to use a single multimode laser with two modes having the right frequency splitting. In all cases, a state superposition is created, and this superposition cannot be coupled to another state with different energy because of destructive interferences between the different paths that can be taken. Hence, photons cannot physically be scattered, and absorption vanishes.

CPT is the basis for many early experiments in slow light, such as those described in Ref. [2], [3] and [4].

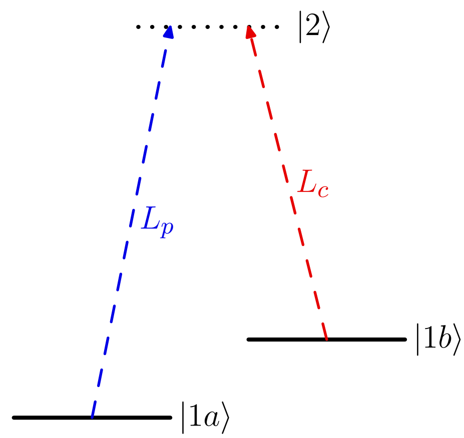



Fig. 4. Coherent population trapping: If the frequency splitting between the two lasers (or laser modes) is right, atoms are forced into a linear superposition of $|1a\rangle$ and $|1b\rangle$. Destructive interferences between the two possible paths prevent photons from being scattered.

### *3.2. Coherent population oscillations*

In Ref. [5], Bigelow *et al.* describe a different quantum mechanism, namely "coherent population oscillations", or CPO, that also leads to transparency in a medium. The basic idea is to use a modulated coupling laser that excites atoms at a given frequency. The atoms are chosen in such a way that the excitation state is metastable (i.e. its relaxation time is relatively large). In some materials, like ruby, the excited state itself is not metastable, but it rapidly decays into a metastable state. The probing laser is also modulated, at a frequency that differs very slightly from the modulation frequency of the coupling laser. Hence, it can happen that a pulse from the probing laser immediately follows one from the coupling laser. If the delay is sufficiently small, photons from the probing laser cannot be absorbed by the medium, because most atoms are still in the metastable state. The name "coherent population oscillations" comes from the fact that the population of the ground state oscillates at the beat rate between the coupling and probing lasers. In Ref. [5], only one laser was used. Indeed, if the intensity of the laser is large enough, it can generate both the coupling and probing light.

CPO was also used by other teams, and was in particular used by Schweinsberg *et al.* [8] to generate slow light (about $25000\,m/s$) and superluminal propagation (propagation at a group velocity larger than $c$, or even with negative group index) in Erbium-doped fiber.

### *3.3. Stimulated scattering*

Kwang *et al.* [6] used yet another technique, "stimulated Brillouin scattering", or SBS, to slow down light in optical fiber. SBS is the result of an interaction between two counter propagating waves: the pump wave and the Stokes wave. For SBS to happen, the wave frequencies must differ by a value equal to the Brillouin shift of the material. When this condition is met, an acoustic wave is generated. This acoustic wave scatters photons from the higher frequency wave to the lower-frequency one. Hence, if the frequency of the pump wave is larger than that of the Stokes wave, the former is slightly depleted by the process, while the latter sees a gain. Since this phenomenon is associated with dispersion in the medium, the Stokes waves is in a situation where it is not only slowed down by the dispersion, but far from being absorbed, it actually gains intensity in the medium. This seems like the dream scenario for slow light. However, dispersion in SBS is not as important as it can be in CPT or CPO, and the lowest group velocity observed to date is of the order of $71000\,km.s^{-1}$.

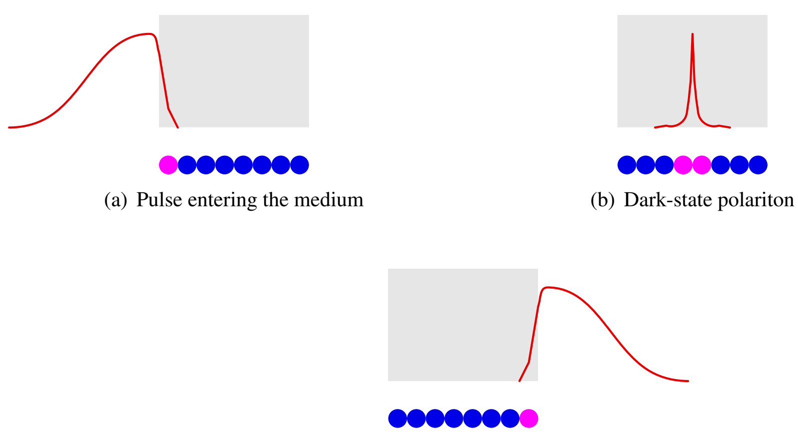
In a similar way, Sharping *et al.* [7] used "stimulated Raman scattering", or SRS, instead of SBS. The difference between the techniques is in the nature of the phonons involved: the acoustic wave of SBS is replaced by vibrational modes in the material in SRS. The latter is a more promising technique for potential applications (see Section 4), as it can accommodate shorter pulses (pulses with a larger spectral bandwidth) than SBS (see also Ref. [19]).

### *3.4. Stopped light*

As we have seen in the previous sections, light can be slowed down substantially through EIT. However, there is a clear limit to EIT techniques: the group velocity of light depends on the slope of the refractive index curve. Whatever the technique used to induce transparency, that slope has a finite value. Hence, light pulses cannot be slowed down to arbitrarily low group velocities.

But once again, if we turn to the underlying quantum effects for help, we realize that it is indeed possible to stop light.

The process goes like this: a coupling laser is turned on in a medium with atoms prepared either in states $|1a\rangle$, $|1b\rangle$ of Fig. 4, or any mix of the two (but at this time, the states are not superposed; they are completely independent). Then, a pulse of the probing laser enters the medium, and is spatially compressed because of sudden low group velocity, a bit like traffic flow can be compressed at a toll booth. However, the peak value of the probe pulse does not vary, so the pulse is essentially losing energy. That energy is in fact absorbed by the medium to create the linear superposition of states described in Section 2.2. The pulse and the superposition of states then travel together inside the medium at the lower group velocity, in what is described in Ref. [11] as a "dark-state polariton". Upon exiting the medium, the transfer of energy is reversed, the pulse is spatially expanded, and it regains its original group velocity. The whole process is schematically shown in Fig. 5.



(a) Pulse entering the medium

(b) Dark-state polariton

(c) Pulse leaving the medium

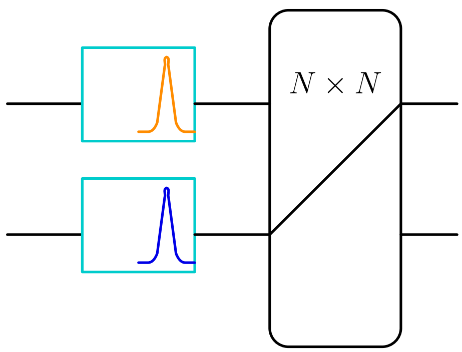
Fig. 5. Dark state polariton: Blue dots represent normal states of the material, while purple dots represent a linear superposition of states. Together with the spatially-compressed pulse, such a linear superposition is called a dark-state polariton. Its velocity is equal to the group velocity of the pulse in the medium.

Now consider what happens if one suddenly stops the coupling laser when the dark-state polariton is fully formed. If decoherence is absent, the information originally carried by the probing pulse is now trapped into the polariton. The latter remains still, as the coupling light driving its movement is not present anymore. Essentially, light has been "stopped", or rather "stored" into the medium. One only has to turn the coupling laser back on to make the polariton move again and to recreate the original light pulse when the polariton reaches the end of the medium.

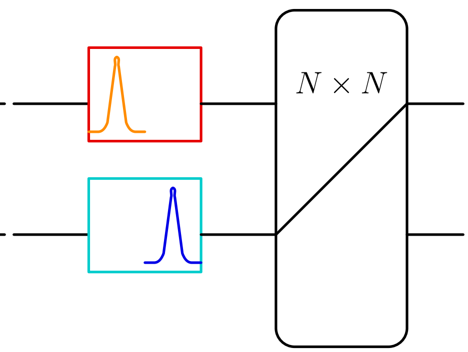
## 4. Potential applications

Like many other aspects of light manipulation, especially if fibers can be involved, slow light has many potential applications in telecommunications. A review of such applications is provided in Ref. [19].

One could legitimately ask how *slowing down* light can be helpful in a domain where in general researchers try to speed things up. The answer is that slow light could be very helpful in some specialized applications, like the prevention of collisions between light pulses. Imagine for instance an $N \times N$ all-optical router, like the one represented in Fig. 6. If both pulses arrive at the same time (Fig. 6(a)), or too close to one another, the router will only be able to accommodate one of them, because of the switch time required to perform operations. In this case, information will be lost, and the overall flow of information will be slowed down. By activating the slow light medium in one of the branches, one of the pulses is delayed, as shown in Fig. 6(b). In this case, no collision occurs and the flow of information is sped up.




(a) Pulse Collision




(b) Delayed pulse

Fig. 6. The ability to selectively slow down light in one input branch of an all-optical router could paradoxically speed up the flow of information, as collisions are prevented. Blue boxes indicate an unactivated slow light medium, while the red box indicates that the medium is activated.

A very interesting potential application of stopped light is the possibility of storing information carried by light pulses, leading to a potential all-optical computing system. Current semi-conductor materials used in computing devices are reaching some of their limits, and an all-optical system would potentially enable us to go further in size reduction and calculation speeds.

In addition, some of the effects of matter-photon coupling used in slowing down light could potentially be used to create entangled photon pairs, leading to quantum-computing capabilities that would go way beyond the capabilities of current computers.

## 5. Conclusion

Even though theory has long predicted the possibility to slow down light, it is only recently that practical ways of doing so have been devised, thanks to quantum effects leading to electromagnetically induced transparency in various media. The same quantum effects have then been refined and have enabled research teams to stop light and “revive” it after a brief instant.

Such behavior leads to a new realm of possibilities in telecommunications and information technology. But the path leading to commercial applications is very long. The main obstacle is the tendency of quantum states of matter to decohere rapidly. Although studies of these phenomena are under way (see Ref. [20]) and hopes are high that some of these limitations will be overcome in the future, it is certainly a very exciting field that will require careful study for many years to come.