Review of Current Methods and Techniques for the Manipulation of Slow Light

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The propagation of the speed of light in a vacuum has been defined to be at $c \approx 3 * 10^8 m/s$. Over the past century, various techniques have been devised to decrease the group velocity of light. In particular, researchers have been attempting numerous methods to bring the speed of light down to non-relativistic speeds. Potential applications with slow light are enormous, but current research has not been able to reach the stage of commercial applications of slow light. There remain many challenges in reducing the speed of light; these issues shall be discussed and addressed, and some potential solutions will be discussed.

I. INTRODUCTION

Decreasing the speed of light has been a constant field of research over the past century. Experimentalists working with slow light have mentioned its potential opportunities. Slow light is of great interest because of the potential to use modulation of the group velocity in electronic systems. Theorized applications include all-optical buffers, ultralow V_π optical modulators, and variable true time delay[1], as well as applications in quantum information processing [2]. Reduction in noise and decreases in power requirements follow. Currently the internet relies on optical fibres carrying light at various wavelengths and frequencies. Separation of these various pulses of light requires conversion to electrons, and this conversion speed is limited by the speed of hardware. With slow light, such an electrical conversion will not be needed, potentially increasing the speed of the internet by orders of magnitudes. This could potentially benefit new research, since the dependency on obtaining data quickly is more important than in the past. Prior to the 1990s, the speed of light in a medium was thought to always be governed by the law of refraction, $v = \frac{c}{n}$, where c is the speed of light and n is the refractive index of the medium in question. Upon entering a medium, light will bend by Snell's Law,

$$\frac{\sin(\theta_1)}{\sin(\theta_2)} = \frac{v_1}{v_2} = \frac{n_2}{n_1} \tag{1}$$

where θ denotes the angle of incidence and the subscripts 1, 2 denote the first and second medium respectively. Upon close inspection, the index of refraction of most mediums is in a range of $\sim 1 - 3$. From this, it is clear that the speed of light can be decreased by at most 67% - less than an order of magnitude smaller than the speed of light in vacuum. This limits the slowing effect of refractive methods. The aforementioned applications of slow light, however, need light that is much slower than $\approx 10^6 m/s$. Here the group velocity is important, with the phase velocity being treated in the classical case where the speed of light in a medium is governed by the index of refraction.

II. MODERN METHODS

In the first widely reported experiment by Hau et al., the speed of light was decreased to 17 m/s [3]. Here a cloud of sodium atoms was cooled and under the effect of electromagnetically induced transparency, light was slowed down. Within the context of slow light, electromagnetically induced transparency causes the medium to appear transparent, but only for certain frequencies and wavelengths. While light will normally not pass through a very optically dense material, under the effects of electromagnetically induced transparency, it is possible to allow light to pass through such dense mediums. Fundamentally, it is a shift from the classical theories of opacity. Using two laser beams, at right angles to each other, with one shining at the cloud of sodium atoms, slow light was observed. Interactions between the laser and the sodium medium produced quantum effects that reduced the group velocity of light. This experiment was repeated again, but this time the cloud of sodium atoms were cooled further, and transitioned into Bose-Einstein condensates. Interactions between the atoms and the photons caused a change in the refractive index, allowing the light to slow down to 17 m/s. Over a narrow region of the sodium atoms, the absorption caused by the excitation of the atoms caused a change in refractive index of that narrow region due to one laser's effect (the coupling laser) on the other (the probe laser, the one that is sent through the medium). Electromagnetically induced transparency is the most widely method to slow down the speed of light. As one of the truly pioneering work in the field of slow light it provided a framework for further research . Experiments involving slow light and electromagnetically induced transparency have become quite common, with the only alternative being that of coherent population oscillations, which will be described below.

Prior to the above experiment by Hau et al., Steve Harris, a member of Hau's team, had managed to decrease the speed of light by a factor of 165. This was a dramatic improvement in the course of four years. In this experiment, electromagnetically induced transparency was also used, but lead vapour was used in place of condensed sodium. Similar processes were carried out, and it was seen that if the probe laser had a small intensity, it would reduce the speed of light to $1.8 * 10^6 m/s$ [4].

Using another method, Bigelow et al. managed to reduce the speed of light to 57.5 m/s [5]. Under their experimental setup, a beam of laser was shined on a ruby crystal. This allowed light to be slowed down by the method of coherent population oscillations, creating changes in the refractive index temporarily. Like electromagnetically induced transparency, coherent population oscillations also creates a transparent medium. But unlike electromagnetically induced transparency, it uses different transitions and interactions of the photons with the medium. A narrow spectral hole causes changes in the refractive index over a narrow region. When pulses of light passes through the medium, the group velocity of light is slowed down.

In a later experiment, still by Bigelow et al., Two beams of laser light was shone at Cr^{3+} ions in a $BeAl_2O_4$ crystal lattice. Differences in the frequency of the two beams of laser caused coherent population oscillation which changed the internal oscillations within the crystal lattice, creating a spectral hole. This allowed for a decrease in the speed of light by many orders of magnitude (91 m/s) [6]. A similar experiment was done, which allowed for fast light, but this is not an area of interest for this paper.

The first practical framework for slowing down light in a semi-conductor was provided by Ku et al. [1]. Pulses of light was shined on quantum wells mounted on a sapphire disk with their substrate removed. The quantum wells were at a temperature of 10 kelvins, a marked improvement over older methods. Attempts to generate slow light in a semiconductor were successful, with speeds as low as 9600 m/s. Since slowing light down via coherent population oscillations only relies on the time it takes to split the beams, this is a remarkable advancement over electromagnetically induced transparency This paves a way for future commercial applications of slow light in semi-conductors. Prior to the work of Ku et al., decreasing the speed of light was just the real world test of existing theories. It should be clear that decreasing the speed of light has now reached the potential for mass commercial applications

There have been various attempts at stopping light. It has been shown that under the influence of electromagnetically induced transparency, it is possible to stop light for 1 millisecond [2]; a non insignificant amount of time. Pulses of light were contained within a cloud of sodium atoms. Excess energy in the photons was absorbed by the cloud of sodium atoms. It was shown that light in such a medium had a much lower energy than light in a vacuum. This would allow for decreases in energy consumption in modern applications.

III. DISCUSSION

Limitations on slowing light down are enormous at the current stage of research. While decreasing the group velocity of light can be done fairly easily, practical applications are still limited by current issues in using the mediums.

In order to cause an electromagnetically induced transparency on a medium, it has the be cooled to less than 1 Kelvin. This limits potential commercial applications to large industries. Further research is needed in order for electromagnetically induced transparency to be a viable method of slowing down light. Methods involving electromagnetically induced transparency also include problems with the medium itself. In the case of Harris et al., the use of lead gas is not a reasonable alternative to using temperatures near absolute zero. Bose-Einstein condensates are not known to be readily available, and the usage of supercooled atoms as a medium seems largely impractical.

Coherent population oscillation appears to be a viable alternative to electromagnetically induced transparency While coherent population oscillation has not produced results as remarkable as those of electromagnetically induced transparency, it lacks the technical limitations inherent in electromagnetically induced transparency. Bigelow et al.'s research suggest that only changes in frequencies of the laser bear or their intensity are needed to provide slow light. The simplicity in coherent population oscillation may provide the alternative answer needed to slow light. The use of non-exotic materials allows for further developments in slowing down light.

There have been few reports of alternative methods to slow light. The lack of alternatives seem to stem from the fact that there are only a few mediums known that can be used to trigger photonic effects between the photons in light and the atoms in the medium. Perhaps further research is needed on the behaviour of light within narrow regions to ensure creations of more methods to reduce the speed of light.

IV. CONCLUSION

Commercial success for slow light largely depends on the works of researchers such as Ku et al. Groundbreaking research is needed to ensure further successes in slowing down the speed of light. While commercial applications are limited at the moment, it is clear that the potentials for reducing the speed of light will be enormous.

Research is moving at a steady, with refinements that have allowed for the decrease the speed of light in a few commercial applications, such as one being tested by IBM. IBM has managed to slow light down in a semiconductor chip [7]. By sending light down altered silicon called photonic crystal waveguides, the speed of light was reduced to $\approx 10^6 m/s$. Applications are still under development by IBM, but this is clearly a step away from electrical components and towards components that function based on light. This may perhaps be a step away form electromagnetically induced transparency and coherent population oscillation. Potential benefits include reduced energy consumption of hardware and reduced delays caused by conversions between light and electrons. Further research will be needed in order to provide more opportunities for commercial products to use slow light while still remaining commercially viable.

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