Chapter 1

Introduction and Literature Review

1.1 The strange interactions of light and matter

Some of the phenomena displayed by light appear counter-intuitive. Ever since Max Planck introduced the word ‘quantum’ into the physicists lexicon, new, almost bizarre demonstrations of how light interacts with matter are reported in the literature week after week. In recent years the cooling and trapping of atoms with lasers has had perhaps the greatest impact on atomic physics of any contemporary development. The idea that a laser, a device traditionally associated with ray guns and burning and heating things, can actually *cool* seems to go against common sense. Yet quantum mechanics says that ray guns can cool to temperatures only a little above absolute zero.

Another of the strange interactions of light and matter is the topic of this thesis: Electromagnetically Induced Transparency (EIT). EIT theory says propagate one laser beam through a medium and it will get absorbed; propagate two laser beams through that same medium and neither will be absorbed. A quite literal trick of the light turns an opaque medium into a transparent one. The magic doesn’t stop there though. EIT can be used to make media behave in quite unexpected ways, some of which will be investigated in this thesis. One of the main impetuses to work on EIT is another counter-intuitive phenomena called Lasing Without Inversion, a process by which laser action is achieved without the need for the condition, learned in every introductory laser class, of population inversion. In fact Lasing Without Inversion would seem to violate the second law of thermodynamics! Yet it can be achieved, although not without some difficulty.

All such phenomena, of course, are described by theories that describe how light and matter interact. In its simplest sense the processes we shall meet in the course of this work are caused by interference, analogous to that seen in water waves, or in Young’s Slits. The difference is that here the interference occurs *within the atoms themselves*. As with experiments in which waves interfere, we will see that coherence plays a large role. We require the light going through a pair of slits to be coherent in order to see a well-defined interference. So too, within the atom, must the properties of coherence come into play, now not of the light wave but of the quantum wave. As such, we require coherent light sources, lasers, to carry out EIT experiments. It has been the development of lasers that has allowed the study of a multitude of light-matter interactions. Of particular interest here are the effects of illuminating atomic vapours with laser light. It is possible to induce optical transitions where the response of the atom retains a distinct phase relationship with the applied optical field. If the atoms are isolated (as in a vapour) then they can retain this relationship for a length of time approaching the atomic decay time, meaning that coherent phenomena can be observed. EIT is one such process, a result of *quantum interference*.

1.2 Coherent Processes

1.2.1 Rabi Oscillations

Rabi Oscillations are a consequence of coherent excitation of an atom by a monochromatic (or near-monochromatic) light source, resonant with an atomic transition. The effect of constant radiation on a group of atoms, on a time scale much less than the natural lifetime of the excited state, can be seen in figure 1.1. The interesting point to note is that the population all ends up in state 2. This is different from a rate equation approach where the atomic medium would become saturated (half the population could be pumped into the upper level but no more). Instead the population continues to be pumped into level 2. Stimulated emission will then begin to take over and the population will be pumped out of level 2 and back into level 1. This cycle of excitation and de-excitation will repeat, so long as the applied field remains constant. Closer examination of the way in which the populations change show that they oscillate sinusoidally with a constant frequency. This frequency is called the *Rabi frequency.* The Rabi frequency is derived using a quantum mechanical treatment of the atom, based on the probability of a transition taking place at a given time [1-3], rather than the more phenomenological approach used in Einstein's rate equations.

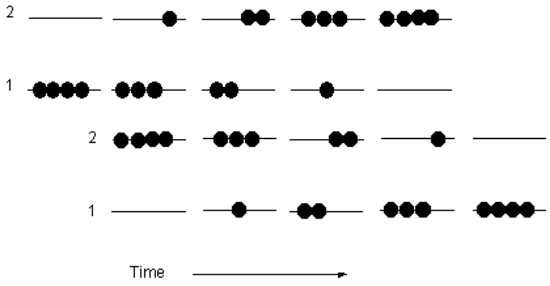

Figure 1.1. *Evolution of the two-level atom with continuous sinusoidal radiation incident upon it – The Rabi atom. Population moves from one level to another until all atoms are in the excited state and then back again. With passing time this pattern repeats sinusoidally.*

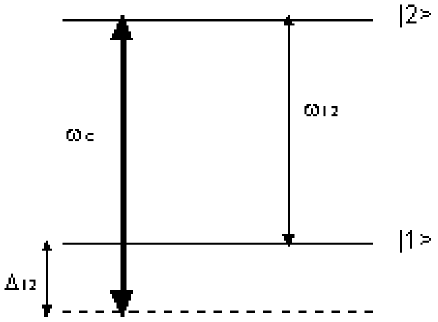

Figure 1.2. *The two-level atom.* ω_c *is the coupling field (exciting field),* ω_{12} *is the transition frequency and* Δ_{12} *denotes the detuning from the transition line centre.*

If we examine a two level atom as shown in figure 1.2 then the Rabi frequency may be expressed as Ω_R:

$$\Omega_R = \sqrt{\Delta_{12}^2 + \frac{\mu_{12}E}{\hbar}} \tag{1.1}$$

where Δ_{12} is the detuning (difference between the laser frequency and the transition frequency), μ_{12} is the dipole element for the transition and E is the field strength of the laser. It should be noted that the Rabi frequency as written is an angular frequency and that as the detuning is increased away from resonance the Rabi frequency will increase and as such the period of Rabi oscillations will decrease. Thus a field far detuned from resonance will have no effect on the atom as we would expect. The Rabi frequency has a ubiquitous presence in quantum optics. Shore [2] outlines a few of its uses: a measure of interaction strength (the role in which it is employed in this thesis), a frequency of population oscillations, a nutation frequency and an optical Larmor frequency among others.

1.2.2 Autler-Townes Effect

In 1955 Autler and Townes demonstrated the ac equivalent of the dc-Stark effect [4]. Using a rf field they split an absorption line in OCS (carbonyl sulphide) into a doublet (figure 1.3a). In order to observe this splitting they probed the rf transition with a microwave frequency field, and observed how the rf field affected the probe. The result is a characteristic doublet absorption trace (figure 1.3b).

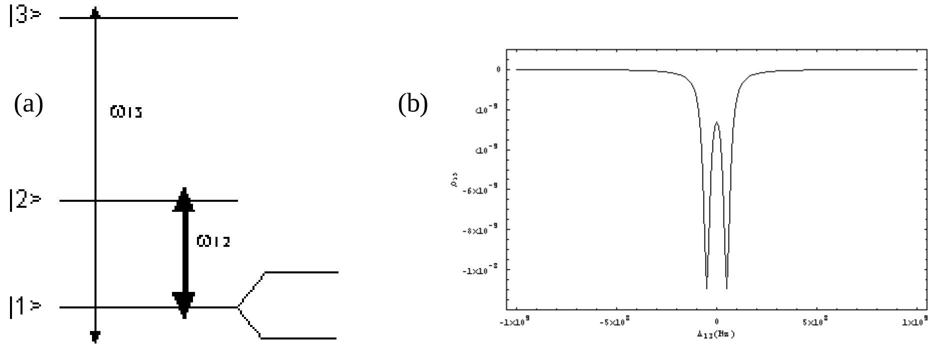

Figure 1.3. *(a) The Autler-Townes experimental set-up is shown. The lower level, |1>, is split by the strong coupling field, ω_{12}. The absorption profile, with the characteristic doublet, of the probe field as it is scanned across level |1> is shown in (b).*

The splitting (also called ac-Stark splitting or dynamic Stark splitting) of the level that occurs is directly related to Rabi frequency. Indeed in a non-Doppler broadened system with the probe field exactly on resonance with the atomic transition the splitting induced by the field equals the Rabi frequency as given by equation (1.1) with Δ_{12}=0. The splitting in this case is symmetric about the resonance point. In cases where the applied field is off-resonance with the transition the splitting will be asymmetric (figure. 1.4).

The importance of Autler-Townes splitting to EIT experiments is that EIT will enhance the depth of the hole that is produced by the Autler-Townes splitting. Quantum interference occurs between the Autler-Townes components and deepens the hole. The two effects work in tandem to make the medium transparent. The ingredient that separates EIT from Autler-Townes splitting is the level of dephasing that the system suffers from. If the dephasing on the unlinked transition (e.g. |2> - |3> in figure 1.3(a) above) is not small enough then Autler-Townes splitting is the effect that is observed and not EIT.

Work on Autler-Townes splitting continues to this day [5-8] with more emphasis on work in the optical regime, which in some cases may be mistaken for EIT. It also has import for work on double resonance spectroscopy [8, 9].

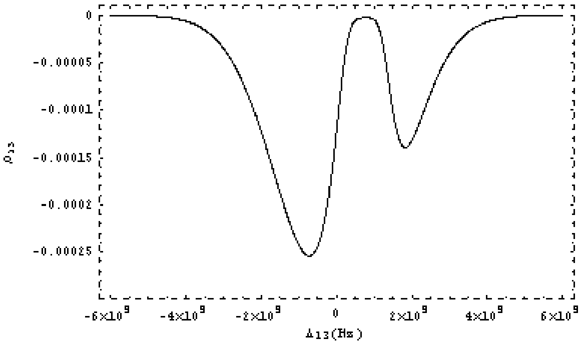

Figure 1.4. *The Rabi splitting is seen to be asymmetric about line centre when the coupling field is not resonant with a transition.*

1.2.3 Fano Interference

The foundations of EIT were laid in an experiment carried out in 1961 by U. Fano [10], which was the first coherence interference experiment. Fano's findings are outlined in figure 1.5.

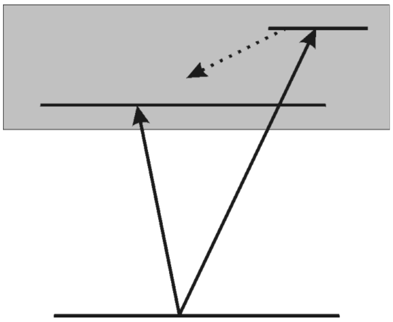

Figure 1.5. *Fano Interference: Two excitation paths to the same ionising state within a continuum leads to a cancellation in absorption as the two paths destructively interfere.*

Excitation takes place between some lower state and a continuum ionising state. It also takes place between the lower state and an autoionised state. Once in the autoionising state the atom relaxes to the ionising state. Hence there are two routes to the final state. Fano found coherent interference between these two routes led to asymmetric peaks in the excitation spectra. Furthermore he found that the 'transition probability vanishes on one side of the resonance'. Coherent interference had turned off the absorption in the medium.

1.2.4 Coherent Population Trapping

The ability to turn off the absorption can also be used to trap population in a particular level, after all if no population is moving from one level to another when under normal circumstances it should, then it can be thought of as being trapped. The extension of Fano's findings to this end led to the idea of coherent population trapping (CPT) [11-13]. This was predicted by Gaspar Orriols and Ennio Arimondo at the University of Pisa in 1976 [14], based on experiments Orriols and co-workers had done [15], where the elimination of fluorescence from an illuminated sodium cell was observed. They found that using a multimode laser the fluorescence disappeared when the mode spacing was made equal the hyperfine spacing of the excited transitions (figure 1.6 gives a schematic of the atomic system they used). The fluorescence was absent due to the fact that the population had been trapped in a lower lying state, unable to move into the upper state.

Coherent population trapping is commonly carried out in the so-called lambda scheme (see Chapter 2) shown in figure 1.6. The initial atomic state can be thought of as a superposition of the lower two ground states. It is then possible to arrange the fields applied to the system so that the probability amplitude for being in the upper state is zero and hence the population remains trapped in the lower two states. This is due to the destructive interference between the two routes allowed to get to the upper state, e.g. |1>-|3> and |2>-|3>.

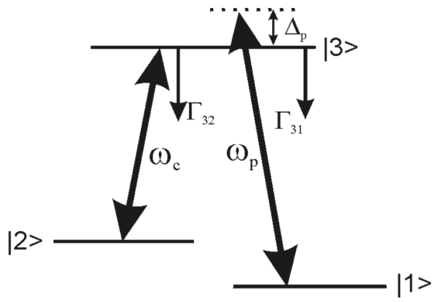

Figure 1.6: *Level Scheme for coherent population trapping (the Lambda Scheme). Typically levels |1> and |2> are hyperfine levels in the same ground state and as such are both populated. Also it is typical that both the applied fields are of similar strength.*

Hence CPT can be explained by considering two of the eigenstates of the Hamiltonian of the atom-field system. These are coherent superpositions of the lower two levels:

$$\left|coupled\right\rangle = \frac{\Omega_1}{\Omega_x}\left|1\right\rangle + \frac{\Omega_2}{\Omega_x}\left|2\right\rangle \tag{1.2}$$

$$\left|uncoupled\right\rangle = \frac{\Omega_2}{\Omega_x}\left|1\right\rangle - \frac{\Omega_1}{\Omega_x}\left|2\right\rangle \tag{1.3}$$

where $\Omega_x = \sqrt{\Omega_1^2 + \Omega_2^2}$. No component of the upper level |3> appears in these equations. One of these happens to be coupled to the upper state through the electric dipole interaction (|*coupled*>) and the other remains uncoupled (a ‘dark’ state). When the fields strengths (Rabi frequencies) of the coupling fields are set in the appropriate ratios the negative sign that appears in equation (1.3) will result in the dipole moment from the |uncoupled> state to the upper state |3> disappearing (<uncoupled|μ|3>=0). This is CPT and it is this effect which underpins EIT.

CPT was experimentally demonstrated by Orriols’ Pisa group [11] and by Carlos Stroud’s Group at the University of Rochester, New York [13]. In fact the phenomena as witnessed by the

Rochester group was seen as an adverse effect. They were trying to maximise the population extracted from the ground state. Unfortunately neither group actually examined what happened to light passing through the cell, instead looking either at florescence or populations. This was despite the fact that both groups had predicted that the absorption would be turned off. If they *had* checked then the first observation of EIT would have been made in the 1970's.

1.2.5 Physics of Electromagnetically Induced Transparency

The Coherent Population Trapping Analogy: EIT is essentially a 'subset' of the coherent population trapping phenomenon, the two-effects being very closely related [12]. In CPT the two fields interacting with the atom are close to the same strength and as such the interference effects arise from both fields. In EIT one of the fields is much weaker than the other i.e. $\Omega_1 << \Omega_2$. Thus EIT is due to only to interference effects driven by the stronger of the two fields, the so-called *coupling* field. The weaker field is termed the *probe* field. Using the same lambda scheme for EIT that we used for our CPT explanation we see that the idea is essentially the same. The difference is perhaps in the details. CPT, in general, has the levels |1> and |2> as either Zeeman or hyperfine levels within the ground state of the atom. In EIT these levels are usually discrete electronic states. Thus, in general, one of the levels in EIT will have no population at any time during the process.

Interference between dressed states: A dressed state analysis also leads to the correct EIT result. Here the atom field interaction is considered as a whole so that the Hamiltonian for the system is made up of components including both the bare state atom and the atom field interaction. A dressed state is defined as, 'an eigenstate of the time-independent form of the total Hamiltonian, including interactions' [16]. If we examine the CPT scheme in figure (1.6) then a dressed state analysis leads to the upper two states forming a coherent superposition of states. It is interference between the probe absorption amplitudes to these two states that results in EIT - see figure 1.7. The CPT analogy and the dressed state explanation for EIT can be related to each other, see for example [17].

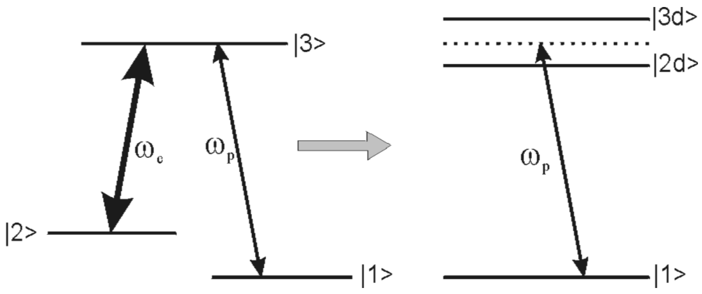

Figure 1.7: *Lambda scheme in dressed basis. The two dressed states are labelled |3d> and |2d>. It is destructive interference between the probe absorption amplitudes that leads to EIT.*

Multiple routes to excitation: Descriptively the simplest explanation, the multiple routes to excitation model of EIT is analogous to the Young's Slits model for interference of light. Here we describe EIT as an interference between two routes to excitation of the upper probe level (e.g level |3> in figure 1.6). The probe can excite population by the |1>-|3> route. An alternative pathway within the atom for population to reach |3> is |1>-|3>-|2>-|3> in which the population is moved between |2> and |3> by the coupling field. We can then think of the two routes to excitation interfering to cancel the original absorption |1>-|3>. Such multi-pathway interferences can also be examined using density matrix perturbation chains, which may also allow additional insight [18].

Other explanations: Other alternatives for explaining the EIT process have been proposed such as the use of Feynman diagrams to represent the interfering processes [19], use of a 3D vector model [20] or methods involving stochastic wavefunction diagrams [21].

1.3 Electromagnetically Induced Transparency

The foundations of EIT were laid by Kocharovskaya and Khanin [22] in 1988 and independently by Steven Harris of Stanford University in 1989 [23]. It is generally the Harris paper that is referenced as the beginning of the EIT literature (mainly because Harris' paper was published in the American *Physical Review Letters* and not the more obscure Russian journal *JETP Letters* that the Kocharovskaya paper appeared in). Both papers addressed a concept known as Lasing Without Inversion (See section 1.4.1). This is a process in which a laser can be made to operate without the usual necessary population inversion by means of atomic coherence. This work was quickly followed by a paper on a similar concept by Marlan Scully of Texas A&M University [24]. EIT was first referred to by name by Harris in a 1990 paper in which another effect based on EIT was proposed, namely the enhancement of nonlinear processes (see section 1.4.2) [25]. The first demonstration of EIT followed in 1991 again by the Harris group [26]. This experiment was carried out in a Lambda scheme in strontium vapour using pulsed lasers, as shown in figure 1.8.

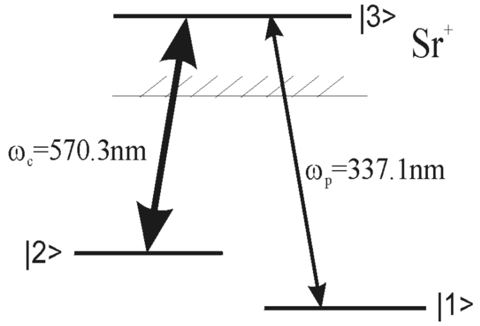

Figure 1.8: *First EIT level set-up in strontium. The coupling field wavelength is 570nm and the probe at 337.1nm.*

The authors were able to able to show that the transmittance of the probe field, which couples between a lower lying state and an autoionising state, could be increased from exp(-20) without the coupling field to exp(-1) with a coupling field present. They point out the importance of the quantum interference in this increase, if there were no interference process present then the transmittance would only have increased to exp(-7). Another important point to realise is that what is observed is in fact interference and not some sort of hole-burning or saturation effect. One could for instance imagine that if all the population were in some way removed from the lower probe level then obviously there would be a reduction in absorption. But this is *not* what happens as the probe field is kept sufficiently weak so as not to cause significant population movement. This experiment carried out in strontium was followed by a demonstration in a cascade scheme in lead vapour [27]. The work in lead has been expanded by Kasapi [28] as a technique for enhanced isotope discrimination. This works by using EIT to make one isotope of lead transparent to a probe field while another remains opaque. Kasapi showed that 0.03% of Pb-207 could be clearly seen against a background of Pb-208.

Subsequent work by Harris' group examined the dispersive properties of EIT [29]. They showed that since the absorption of the medium is modified the refractive index must be as well. They found that at the point where the absorption is swept through a zero the refractive index varies rapidly with probe frequency (i.e. dispersion) and that this implies a significantly reduced group velocity near the zero probe detuning position. This work laid ground for subsequent ideas about slow light (section 1.4.3.3). In their experiment Harris' group demonstrated a reduced group velocity due to EIT of c/250 but they did not measure the dispersion directly. This experiment was carried out by the Xiao group [30] who measured the dispersion of the medium using a Mach-Zehnder interferometer technique [31]. They observed reduced group velocities of c/13.2.

Other experimental work on EIT includes further work by the Min Xiao group from Arkansas. They have studied continuous-wave EIT in rubidium vapour in work that has close connections with that done at St. Andrews in the past. They have examined the use of EIT as a spectroscopic tool [32] in which an EIT resonance is seen on each of the hyperfine levels that make up the upper coupling field state. This has also been explored by Moseley *et al* in which the technique is compared with two-photon spectroscopy [33]. Further studies have included general investigations of EIT in cascade schemes [34-36] and lambda schemes [37]. The change in EIT as the coupling laser linewidth increases has also been explored [38]. The authors found that as the linewidth of the interacting laser increased the EIT effect degraded due to an increase in the dephasing of the system. This experiment was followed by another looking at the effect of linewidth on the probe field [39]. In this case it was found that only the components of the probe field that were resonant with the probe transition were able to pass through the medium. Off-resonant components were absorbed. More recently this group have looked at building an 'electromagnetically induced grating' [40]. This works by having a strong coupling standing wave, interacting with three-level Lambda-type (or cascade-type) atoms. This can diffract a weak probe field (propagating along a direction normal to the standing wave) into high-order diffractions. By taking advantage of the absorption and dispersion properties of electromagnetically induced transparency the authors have demonstrated an atomic grating that can fan effectively diffracted light into the first-order direction.. They have also considered EIT and AWI effects in four level N-type medium in Doppler broadened media [41], ideas that are in some part related to the work presented here in chapters 6 and 7.

Work carried out in the St. Andrews group has covered similar ground to that of the Xiao group both independently and at similar times. As has already been mentioned Moseley *et al* [33] investigated uses of EIT for spectroscopy. In the same paper they also clearly showed the nature of the one and two-photon interference effect in EIT. Fulton *et al* [42] showed that EIT is affected by the Zeeman structure of atoms and that EIT resonances can be manipulated once the normal Zeeman level degeneracy is lifted. Further studies of effects due to Zeeman levels in the context of inversionless gain have been carried out by Durrant *et al* [43]. Fulton *et al* [44] also conducted a definitive study of EIT in (cascade, lambda and Vee) three level schemes, showing the roles of, for example, optical pumping in the EIT process. Later work includes investigations into the ability to mismatch the wavelengths of the probe and coupling fields in Doppler broadened EIT both in the case where the probe field wavelength is longer than that of the coupling field [45] and where the probe field has a shorter wavelength than the coupling field (the so-called up-conversion regime) [46], a theme which is further explored in chapter 3. Some of the most impressive work carried out in the St. Andrews group was the discovery of the Electromagnetically Induced Focussing effect [47, 48], in which the spatial variation of the coupling field results in the probe field seeing the coupling field as a lens. This is discussed further in section 1.4.3.2.

Other work has proposed using EIT as a method of eliminating band gaps in resonant optical materials [49]; producing a three-level medium whose quantum mechanical state is a function of position [50]; enhancement of third harmonic generation [51]; generation of a wide spectrum of Raman sidebands while improving propagation through a inhomogeneous medium [52] and the related phenomena of subfemtosecond pulse generation by strong coherences in molecules [53]. EIT can also be used to eliminate self-focussing within an atomic sample [54]; has the potential to utilise optical fields to coherently control Mössbauer spectra [55] and possibly in the measurement of atomic parity nonconversion [56]. Proposals have been made to narrow laser linewidths and improve properties of optical resonators and laser devices by using EIT within the cavities (intracavity EIT) [57]. Along with normal gaseous media EIT has been investigated in RF discharges [58], cold atoms [59, 60] and atomic beams [61].

As can be seen numerous studies have been carried out into EIT, both the process involved and applications of the phenomena. The references given here are to be seen as an introduction to the subject. For an alternative review of the subject area, which deals much more with, for instance pulsed phenomena in EIT, see Jon Marangos' review [17]. The following sections introduce some of the more important areas that result from EIT, including EIT in solids, which is now of increasing interest, Lasing Without Inversion, enhancement of nonlinear processes, refractive index effects (including slow light) and electromagnetically induced absorption [62].

1.3.1 EIT in solid media

The majority of EIT experiments are carried out in gaseous media, rubidium [44], caesium [63], hydrogen [64] and the like. For many applications, however, the ability to carry out EIT in solid materials would be beneficial (see for example section 1.4.3.3 on slow light) particularly if we wished to take EIT 'into the field'. However in considering solid materials we run into problems. The question can be put as follows: Can EIT be used to realise X-ray vision? The answer is no. The major problem lies in the very broad linewidth transitions and/or the large dephasing rates that occur in solids. In EIT we require a coupling laser field strength rivalling the probe transition linewidth. For this to occur in solids we would require laser strengths that would burn a hole through the material. Not *quite* what we mean by X-ray vision! Some of these problems can be circumvented by cooling the sample down near to absolute zero. This has resulted in the observation of EIT in several solid materials. The first demonstration was carried out in ruby [65] by Zhao *et al* and is also notable for the fact that the coupling field in this experiment was a microwave field rather than an optical field, but this particular experiment has been somewhat disputed. Other similar experiments have been carried out by Ichimura *et al* [66] and by Ham *et al* [67]in Pr^{3+}:Y_2SiO_5. This second group, who are at MIT, have carried out a number of experiments investigating enhancement of four-wave mixing in solids due to EIT [67], the possibility of optical data storage using EIT in solids [68, 69], gain induced by rf fields [70] and line-narrowing effects useful for spectroscopy [71].

Other interesting work on EIT in solids has been carried out by a group at the Australian National University in which they explore EIT effects in a nitrogen-defect centre in diamond. Recently they have shown the dynamic Stark splitting of an EIT resonance [72, 73], in which they split the EIT window into two or more separate lines, a effect similar to that explored in chapters 6 and 7. These effects are slightly different from other EIT experiments in that they are carried out at ESR frequencies rather than at optical frequencies and so further circumvent some of the problems associated with EIT in solid media. As such they have great potential in investigating proof of principle type experiments.

We note that in theory many ion doped crystalline solids may be suitable for EIT. Whether or not they offer any particular advantage over each other is debatable. You always lose out on the dephasing. However some people remain optimistic. A group of Japanese researchers from Toshiba (US Patent 6028873) have recently patented the idea of an inversionless laser (see section 1.4.1) (which uses EIT to work) with a solid medium as the gain material. They list well over 100 possible candidates for the gain medium which makes the patent cover a multitude of potential devices. Somebody is obviously hopeful that one day EIT in solids will become such a practicality that devices will be able to be based upon the idea.

1.3.1.1 EIT in semiconductors

Semiconductor devices may hold the key to applied inversionless laser devices. Since they can be engineered to specific designs there are fewer constraints on semiconductors than in other media. They also have the potential to be used as sensitive detectors in spectral regions where detection is difficult and also to improve existing properties of current semiconductor devices. Various groups have considered EIT-type effects in semiconductors including the Imamoglu group at the University of California, Santa Barbara. They have investigated Fano interference in double quantum well structures [74] similar to the one shown on the right-hand side of figure 1.9 (without the field α). Such schemes make use of quantum tunnelling to couple between the two wells. Schmidt and Imamoglu [75] have also considered using EIT to enhance nonlinearities in semiconductors, with potential in areas such as optical parametric generation or frequency generation. Schmidt and Ram have explored the possibility of creating an all-optical wavelength converter and switch based on EIT [76].

Other work includes that by Pötz [77] who looked at EIT type effects in double well structures where the probe field is controlled by a microwave field. Another recent proposal has been that of Yelin and Hemmer [78] in which EIT in a semiconductor can be used to detect far infrared radiation (around 10microns) by observing a shorter wavelength probe field. The process relies on a four-level system shown in figure 1.9.

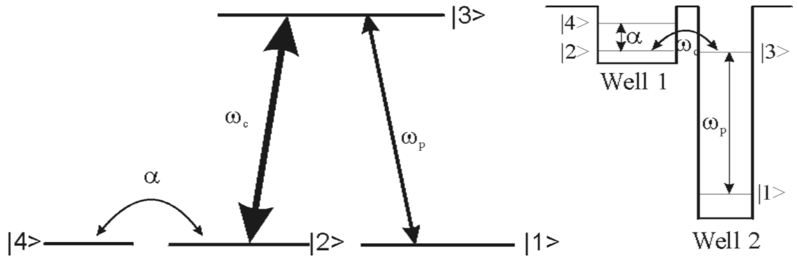

Figure 1.9: *EIT scheme for the detection of long wavelength radiation in a semiconductor. The EIT is set up via the the probe (ω_p) and coupling (ω_c) fields. It can then be destroyed via the application of a third field, α. This third field has a longer wavelength than that of the probe and hence a technologically 'easier' wavelength can be used to monitor the technologically 'hard' wavelength.*

Normal EIT is produced by the coupling field ω_c on the probe field ω_p. Then the EIT can be destroyed, producing a re-absorption of the probe, by the application of a third field α. We can engineering the quantum well structure so that ε lies in the visible region and α in the far infrared. Thus this provides a novel detection technique for the far infrared light. The destruction of EIT in multilevel EIT systems is examined in greater detail in chapter 6.

Other workers have predicted inversionless lasers based on EIT in semiconductors. These include Zhao *et al* [79, 80], who predict LWI effects in system similar to that shown in figure 1.9 above, and Imamoglu and Ram [81] who predict LWI effects in the absence of a coupling field. They instead rely on the resonance between sub-bands in different quantum wells. This, they show, is identical to the original lambda scheme proposed by Imamoglu and Harris [82].

A more thorough review of experiment and theory of EIT due to quantum tunnelling in semiconductors can be found in [83].

A recent experiment by a group at Imperial College has demonstrated EIT in a quantum well structure for the first time [84]. The energy levels used are two close lying states in the same quantum well (i.e. no tunnelling process is required). The level structure is shown below in figure 1.10.

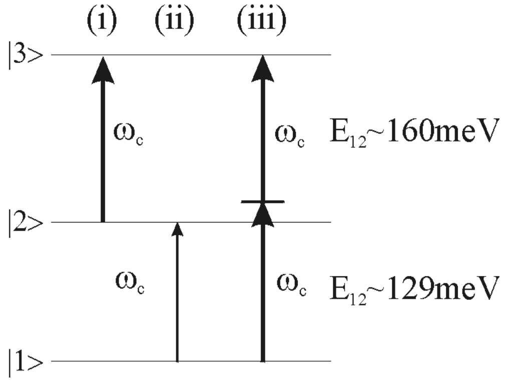

Figure 1.10: *Level structure for observation of EIT in a quantum well cascade scheme. The two transitions are closed spaced in energy allowing for three different coupling regimes: (i) EIT, (ii) Strongly driven two level atom and (iii) phase-locked coherence. The probe field resonant with the |1> -|2> transition is not shown.*

As can be seen the fact that the two transitions are quite closely spaced allows the coupling field to interact with the system in a variety of ways. The first is a normal EIT effect, shown in figure 1.10(i). The second effect is analogous to the strongly driven two-level atom and the third corresponds to an effect the described as ‘phase-locked’ EIT. This third condition corresponds to the case where the coupling field is two photon resonant with the |1> - |3> transition and was found to produce the biggest EIT effect.

1.4 Applications of EIT

1.4.1 The Inversionless Laser

The concept of an inversionless laser is an intriguing one. If we examine Einstein’s rate equation approach of laser theory then it should be impossible to achieve laser action without a population inversion, as Siegman points out [85]:

> ‘For laser action to occur, the pumping process must produce not only the excited atoms, but a condition of population inversion…It turns out we may obtain this *essential condition of population inversion* in many ways…’

So counter-intuitively it seems an immediate consequence of EIT that inversionless lasers should be possible. Einstein’s rate equation forbids inversionless lasers. A medium will ultimately become saturated when half of the population is in the upper level of the laser transition (and half is in the lower state). Since the medium suffers from stimulated emission as well as stimulated absorption then the medium can never experience laser action without a population inversion, however if the stimulated absorption is turned off, or significantly decreased then it should be possible to have these strange upside down lasers. Such were the proposals by Kocharovskaya and Khanin [22], Harris [23] and Scully [24]. The idea can be examined in the following scheme [86]:

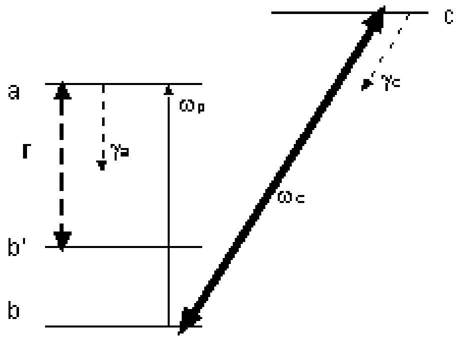

Figure 1.11: *Level scheme for observation of inversionless lasing. The incoherent pump, r, is applied between levels b’ and a. Lasing is observed on the a to b transition. Level a is the* $5P_{1/2}$ *level, level c is the* $5P_{3/2}$ *level and b and b’ correspond to the* $5S_{1/2}$ *(F=1) and* $5S_{1/2}$ *(F=2) levels respectively.*

The major difference between a straight EIT scheme and an LWI scheme is the introduction of the *pumping* term r. As with a normal laser, a pump is required to move population into the upper laser level. In the LWI case the pump is generally termed incoherent, as the linewidth is much larger than the linewidth of the atomic transition that it is pumping. It is desirable to use an incoherent pump, as use of a source that interacts coherently with the system under consideration will necessarily upset the coherences generated by the probe and coupling field. For instance Boon examined the possibility of coherently pumping a Vee-scheme [87] and found that an incoherent pump produced more gain.

For many laser wavelengths the effort that would go into building an inversionless laser would be counter productive. For instance there would no specific gain in building an inversionless 633nm laser over a normal He-Ne laser. The main area of interest in the inversionless laser is short-wavelength lasers. Since the Einstein A coefficient increases with frequency:

$$A = B\frac{\hbar\omega}{\pi^2 c^3} \tag{1.4}$$

so that the spontaneous emission on transitions with short wavelengths is very rapid this means that the atoms undergoing excitation on such a transition will rapidly decay to a lower state. Hence a population inversion is increasingly difficult to establish as the transition wavelength gets shorter. Inversionless lasers open up the possibility of circumventing this problem. Inversionless lasers themselves, however, have problems of their own, in a particular the difficulties involved in constructing them. So far no inversionless laser of technological importance has been demonstrated.

The first proof of principle inversionless laser was built by the Scully group. The same group had previously reported amplification without inversion in Rb [86] and extended their set-up to demonstrate laser oscillation. The experimental apparatus is shown in figure 1.12

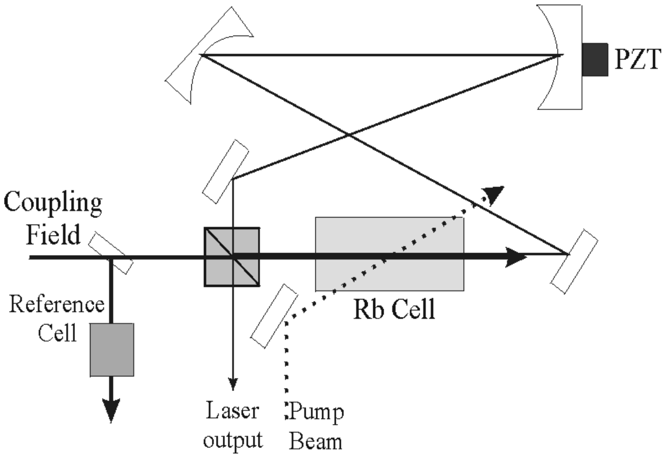

Figure 1.12: *Experimental set-up for observing inversionless lasing in Rb.*

The atomic system is shown in figure 1.11 above. The coupling field is supplied by a single-frequency diode laser resonant with the $5S_{1/2}$-$5P_{3/2}$ transition (the D_2 line). The laser transition is the $5S_{1/2} – 5P_{1/2}$ transition (the D_1 line). The incoherent pump source on the $5S_{1/2} – 5P_{3/2}$ transition is used both to destroy optical pumping due to the strong coupling field and also to act as a pump for the inversionless laser putting a small amount of population into the upper laser transition. A weak magnetic field is used to destroy coherence created by the pump field in the $5S_{1/2}$(F=2) Zeeman levels. When the coupling and pump field come onto resonance, inversionless laser oscillation is observed, the laser field having been built up from cavity noise. The fact that such a system is in fact displaying inversionless gain can be demonstrated by examining the system in the presence of a probe field resonant with the laser transition (the set-up for finding amplification without inversion). In the case where the probe field linewidth is increased so as to become incoherent, the amount of gain decreases significantly indicating that it is a coherent process (i.e inversionless gain) and not a population inversion that accounts for the gain that is observed. The laser output was approximately 30μW at 794nm. Obviously this is not a practical system.

A number of other proof of principle experiments have been carried out, most notably by Peters and Lange [88], Padmabandu *et al* [89], Sellin *et al* [90] and Jong *et al* [91, 92]. Many others have observed amplification without inversion ([93-95] for example) although none with any significant *wavelength mismatch*. This idea of mismatching the lasing and coupling fields is important in the search for short wavelength inversionless lasers, as ideally we would like a technologically 'easy' laser as the coupling field controlling a short wavelength laser transition. One of the main problems with this idea is that as the wavelengths get further and further apart EIT is increasingly difficult to obtain (although not impossible). A good example of such an EIT experiment was carried out by Boon *et al* [46]. This idea of producing a short wavelength laser using a longer wavelength control field is called 'up-conversion' and is discussed in detail for Doppler broadened systems in [96, 97] and also in Chapter 3 of this thesis. A summary of LWI and AWI experiments is listed in table 1.1.

Type	Authors	Medium	Coupling (nm)	Probe (nm)	R
Pulsed AWI	Nottelmann *et al* [95]	Sm Vapour cell (Λ)	570.68	570.68	1
Pulsed AWI	Fry *et al* [98]	Na Vapour cell (Λ)	589.86	589.86	1
			558.43	558.43	1
Pulsed AWI	van der Veer *et al* [99]	Cd Vapour cell (Λ)	326	479	0.68
CW AWI	Kleinfeld and Streater [100, 101]	K Vapour cell (Vee)	766.5	769.9	1
CW AWI	Zhu *et al* [102, 103]	Rb Vapour cell (Λ)	780	780	1
CW AWI	Sellin *et al* [90]	Ba atomic beam (cascade)	554	821	0.67
CW AWI	Fort *et al* [63]	Cs Vapour cell (Vee)	852	894	0.95
CW AWI	Shiokawa *et al* [104]	Laser-cooled Rb (Λ)	780	780	1
CW AWI	Hollberg *et al* [105]	Laser cooled Rb (Vee)	780	795	0.98
CW LWI	Zibrov *et al* [86]	Rb Vapour cell (Vee)	780	795	0.98
CW LWI	Padmabandu *et al* [89]	Na atomic beam (Λ)	589.76	589.43	1
Pulsed LWI	de Jong *et al* [91]	Cd Vapour cell (Λ)	326	479	0.68
CW LBT	Peters and Lange [88]	Ne Vapour cell (double-Λ)	824.9	611.8	1.35

Table 1.1: *Summary of LWI and AWI experiments to date. CW is continous wave, AWI is amplification without inversion, LWI is lasing without inversion and LBT is lasing below threshold. The value of R is the probe field to coupling field frequency ratio. It is therefore a measure of up-conversion.(see LWI review* [106]*)*

Lasing Without Inversion is not just about short wavelength lasers however. Other aspects of interest include various quantum optical effects, such as the inhibition of spontaneous emission noise in inversionless lasers [107] and the production of squeezed laser light [108, 109]. More recently predictions for producing inversionless gamma ray radiation have been made [110-113].

Inversionless lasers offer tantalising possibilities. Compact short wavelength lasers would be a great boon technologically. But over 10 years after the prediction of such devices no substantial breakthrough has been made. The dearth of experimental work in the field shows, not that the idea is of no interest but that the work is very difficult to achieve despite the wealth of theory papers published ([87, 108, 114-131] for example). The defining experiment is out there just waiting to be performed, but many problems remain. For a more complete discussion of LWI, motivations, different theoretical approaches to the phenomena, experimental realisations and difficulties see the recent comprehensive review by Mompart and Corbalàn [106].

1.4.2 Enhancement of Nonlinear Processes

Many nonlinear processes suffer from re-absorption. That is, if a wave-mixing process results in a frequency being produced on a transition that is not coupled to one of the fields driving the process then any radiation at this frequency stands a chance of being re-absorbed by that transition. Since these types of processes generally produce only a small amount of radiation then the problems are obvious. The fact that EIT can provide transitions that do not re-absorb is therefore very attractive. Indeed this idea was one of the original proposals for EIT [25] in which a four-wave mixing process could be enhanced (i.e. the $\chi^{(3)}$ susceptibility is enhanced). A sample atomic scheme is shown in figure 1.13.

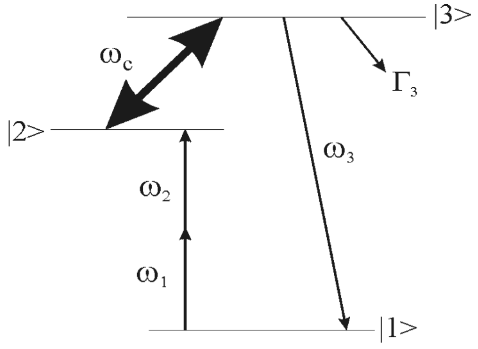

Figure 1.13: *Harris' wave-mixing scheme. The coupling field on the |2>* **-** *|3> transition induces transparency on the wave mixing transition |3>* **-** *|1> and hence reduces the absorption that the generated field would normally experience.*

The first experimental evidence for enhancement of nonlinearities was by Hakuta *et al* [132]. They demonstrated that a dc field could be used instead of an ac coupling field in certain cases. This first experiment was three wave mixing in hydrogen, which is normally forbidden. The same group then went on to demonstrate four-wave mixing schemes in hydrogen [64], producing light in the UV at 103nm, and also sum-frequency generation in a hydrogen discharge [133]. Work at St. Andrews has looked at similar schemes in sodium [134]. Sum-difference frequency mixing in krypton has been performed by the Marangos group at Imperial college [135-138]. Recent work in this area includes four-wave mixing enhancement in a crystal [71], which opens up possibilities of using EIT for applications such as optical data storage in solids.

Another intriguing application of EIT in the nonlinear regime is the possible development of a broad band optical parametric oscillator with a high efficiency [139]. Such a device has been proposed by Harris and Jain. Lukin *et al* [140] have studied enhancement of parametric processes in which pairs of Stokes and anti-Stokes fields can be generated from very small initial values, e.g. the vacuum field. These ideas have been extended to experimentally produce self-oscillating parametric processes [141] – a mirrorless parametric oscillator. Further studies have investigated the properties of such processes [142, 143]. The idea is that two counter-propagating beams, E_b and E_f, drive a double lambda scheme, shown in figure 1.14.

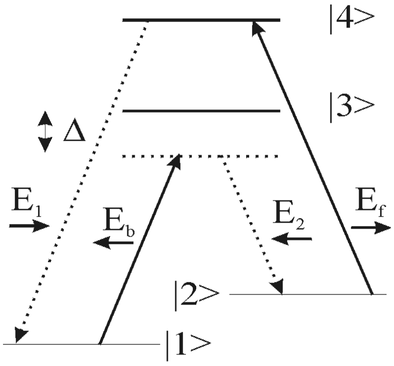

Figure 1.14: *Double lambda scheme used in the mirrorless parametric oscillator scheme. The arrows under the field descriptors (the 'E's) denote the direction of propagation of the fields.*

These fields in turn generate fields (E_1 and E_2) at the Stokes and anti-Stokes frequencies. For an appropriate density length of the medium for a given pump field intensity the system is found to display self-oscillation. Fleischhauer *et al* [142] calculate that such a set-up can be used to produce non-classical photon fields (the photon pairs created in this process are in quantum correlated states resulting in suppression of the intrinsic quantum fluctuations of the light [144]) with very narrow linewidths and low power requirements. This they suggest will be of interest in a number of areas of quantum optics and nonlinear optics.

The enhancement of nonlinear process is the one area of EIT where strong, potentially useful experiments have been carried out. Research in the area continues and it may prove to be that this area of research is the one that benefits the most from quantum interference effects.

1.4.3 Refractive Index Effects

Another topic of interest in quantum interference research is that of the modification of the refractive index properties of a medium. Since the absorption and refractive index of a substance are linked via the Kramers-Kronig relations we see that modification of the absorptive properties of a medium will result in a change in the refractive index properties as well. Examples of uses of this modification are high refractive index media with low absorption (phaseonium), electromagnetically induced focusing and slow light.

In a two level system if we examine the absorption of a probe scanned through the transition we find maximum absorption on line centre. Accompanying this absorption will be a refractive index profile that has a zero coinciding with the maximum absorption. We also see a dispersive element of the refraction (variation of refractive index with frequency) around the maximum absorption point. By moving to a transparent medium we can modify this as shown in figure 1.15. We see that in a transparent medium we have high dispersion (rapidly varying refractive index) and this is the basis for slow light phenomena (section 1.4.3.3) and proposed schemes for magnetometry [145, 146] and line narrowing and frequency stabilisation of lasers [57]. It also allows effects such as Electromagnetically Induced Focussing [47, 48] and optical waveguiding of a probe field [147, 148], discussed below in section 1.4.3.2.

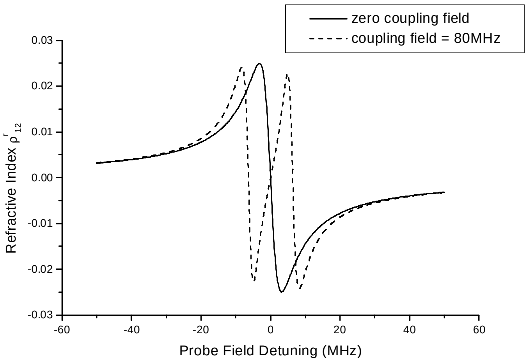

Figure 1.15: *Refractive index as a function of probe field detuning. In the two level case, i.e. no coupling field then we get the classic trace, shown by the solid line. In the case where a coupling field is applied the profile is modified as shown by the dashed line.*

Another refractive index effect due to EIT is that of EIT-induced birefringence. This was first demonstrated by Pavone *et al* [149]. This phenomena is briefly discussed in Chapter 7 when where examine the potential for using EIT-induced birefringence as a method of spectroscopy. Recent work by Patnaik and Agarwal [150] has also shown that birefringent effects in a coherently prepared medium can be used to control magneto-optical rotation.

1.4.3.1 Phaseonium

Phaseonium differs from the highly dispersive media found via EIT in that it is a medium which has a large refractive index with no accompanying probe absorption. It was proposed by Scully [151]. In order to create such a medium (which Scully has called a new state of matter) it is necessary to ‘prepare’ the medium in some way. This preparation may take the form of incoherent pumping akin to that found in inversionless lasing discussed above. Further theory of enhancement of the refractive index can be found in [152-156]. A proof of experiment to observe phaseonium was carried out in rubidium [157]. As expected a region was found in which the absorption vanished accompanied by a large refractive index.

One of the main proposed applications of phaseonium is the development of a high sensitivity magnetometer. If we place a phaseonium medium in the arm of a interferometer then a varying magnetic field will perturb the Zeeman levels of the atomic system. This will detune the probe field slightly and this detuning will alter the refractive index of the medium. This change should be detectable using the interferometer. It is estimated that a magnetometer based on coherently prepared atoms could be 2 orders of magnitude better than a state of the art SQUID magnetometer [158]. Further theory on phaseonium magnetometers can be found in [146] and on other magnetometers based on EIT effects in [159, 160]. Additional advantages in the use of such a magnetometer are that unlike other *optical* magnetometers it can work in the high density – strong field regime potentially allowing a greater signal to noise ratio, and also that it has a larger dynamic range than more conventional devices. Other applications include high-resolution microscopy [158]. The resolution of an optical microscope is given by $n\sin\theta/\lambda$ where n is the refractive index of the lens, θ is the optical collective angle and λ is the wavelength. If we can increase n then obviously the resolution could be increased. The experimental conditions in order to observe such enhancements are difficult to achieve however. A more recent experiment [161] has shown that power broadening of optical resonances can be significantly narrowed in coherently prepared, dense atomic media and that it is possible to observe sub-EIT linewidth effects in such media. Other work on the subject relevant to this thesis has been carried out by Lukin *et al* [162] in which phaseonium can be obtained using so-called *double-dark resonances* with less incoherent pumping than in the case discussed above. Double-dark resonances will be discussed in relation to EIT in multilevel cascade schemes in chapter 6.

1.4.3.2 Electromagnetically Induced Focussing

As we have seen EIT affects both the absorption and the refractive index of a medium. This implies that the stronger the EIT effect, the larger the change in refractive index. We can make use of this fact in normal EIT experiments to develop a new process called Electromagnetically Induced Focussing (EIF). Since laser beams have Gaussian intensity profiles a probe field that has its beam waist matched to the coupling field waist will experience stronger EIT at the centre of the beam than at the edge. The refractive index that the probe experiences will also, therefore, change with the radial intensity of the coupling field. Moseley *et al* showed [47, 48] that this effect implied that the probe field experiences the coupling field as a lens. This is illustrated in figure 1.16.

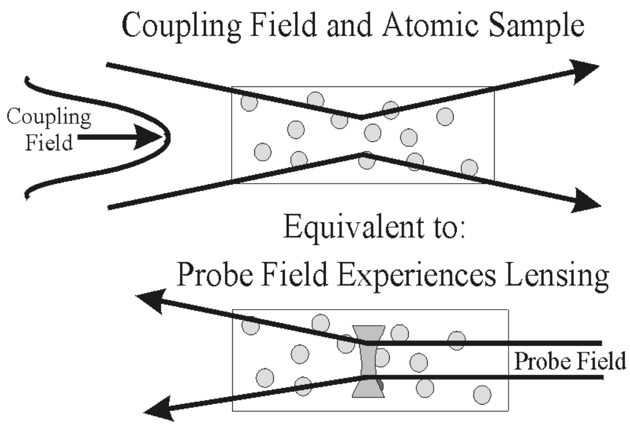

Figure 1.16: *Schematic of Electromagnetically Induced Focussing. The transverse spatial profile of the coupling field results in the probe field experiencing a varying refractive index across its transverse profile. This effect is eqivalent to that of having a lens in the path of the probe field.*

By varying the detuning of the probe field it is possible to have the system act as various types of lenses, e.g. convex or concave. The EIF effect occurs more strongly for tightly focussed beams, where the peak intensity of the coupling field is greater. Therefore when performing such experiments it is important to take into account the EIF effect. Truscott *et al* [163] have used this idea of EIF to produce a waveguide in atomic vapour. Using a Laguerre-Gaussian [164, 165] beam as the coupling field and a normal Gaussian probe field, the probe will experience a high refractive index when it is on line centre with its transition. If the coupling field is red detuned (a negative detuning) it can act so as to guide the probe out of the intense region of the coupling field. If the probe is blue detuned it can act in the opposite way. This results in the probe being waveguided along the Laguerre-Gaussian beam. In essence the refractive profile experienced by the probe is similar to the profile it would experience if it were in an optical fibre. This work has recently been more fully explained by Kapoor and Agarwal using a full density matrix treatment [148].

In this thesis we briefly examine how EIF effects occur in four-level media and how such phenomena lead to the idea of a rf controlled optical lens.

1.4.3.3 Slow Light

The most recent development in EIT research is the idea of ‘slow’ light. This concept was first demonstrated by the Hau group at the Rowland Institute [166]. EIT is carried out in a Lambda scheme in a sodium Bose-Einstein condensate. Due to the very low coupling field required to induced the transparency (the Doppler broadening in the condensate is almost negligible) the transparency peak is much smaller than the natural linewidth of the transition. The dispersion curve is therefore very steep and this results in light propagating at the probe frequency having a very low group velocity, v_g. This is given by:

$$v_g = \frac{c}{n(\omega_p) + \omega_p \frac{dn}{d\omega_p}} \approx \frac{hc\varepsilon_0}{2\omega_p} \frac{|\Omega_c|^2}{|\mu_{13}|^2 N} \tag{1.5}$$

where $n(\omega_p)$ is the refractive index at the probe frequency ω_p and $dn/d\omega_p$ is the change in refractive index with probe frequency (the dispersion). We see immediately that the higher the dispersion (achieved by EIT) the lower the value for v_g. The Hau group reported group velocities as low as 17ms^{-1}, hence the name 'slow light'. EIT had been used to slow light down before, with Harris [29] reporting light with speeds of c/250, but it was the huge amount by which the light was slowed that made the Hau experiment so notable.

Two further examples of slow light followed quickly after the first demonstration of the phenomena but this time in 'hot' media [167]. The Scully group performed their experiment in rubidium vapour at around 360K again using EIT in a Lambda configuration. By a careful choice of experimental parameters such as field strength and atomic density a group velocity of 90ms^{-1} was observed. It was noted that this was an average velocity as the coupling field is absorbed in the cell and the group velocity decreases with the coupling field power. They also note that the 90ms^{-1} is not a lower limit to the group velocity but by further modifications of experimental parameters they could bring the velocity down nearer 10ms^{-1}. An interesting aside that the authors note is that the Doppler free configuration, where the probe and coupling field counter-propagate, that is necessary for observation of EIT effects in so many experiments (including some of those found in this thesis) is not necessary for the observation of low group velocities.

The second 'hot' gas demonstration of slow light was performed by Budker *et al* [168] again in rubidium. In this case the experiment investigated what happened to the polarisation of the light exiting the gas cell if the polarisation of the input light was changed. The authors show that the process is equivalent to EIT and thus that reduced light group velocity is related to nonlinear magneto-optical effects. Light within the cell suffers from a group delay and as such has a low group velocity, which can be controlled by varying the applied magnetic field. It was found to be of the order of 8ms^{-1} in this experiment. This is the lowest published group velocity of light at the time of writing.

Given slow light, what can we do with it? One interesting proposal is that of an optical black hole, an idea put forward by Leonhardt and Piwnicki [169]. The idea is that if light were to interact with a vortex of some sort, e.g. in a Bose-Einstein condensate, then if it were moving slowly enough it would be sucked into the vortex in the same way that matter is sucked into a black hole in space. Thus a black hole that could be built within a laboratory could be possible. This effect arises as light sees a moving dielectric medium as an effective gravitational field. It may be that the vortices recently achieved in Bose-Einstein condensates are too small to work effectively as optical black holes. In that case it may be possible to use Laguerre-Gaussian beams to create a vortex within a sample of hot gas or to carry out EIT within a rotating solid medium.

Many problems exist in all these approaches but a careful experiment in the right medium may well yield results. The analogues between optical black holes and real black holes would then allow black hole and gravitational phenomena, such as Hawking radiation [170], to be studied in the convenience of a laboratory instead of in space.

Leonhardt and Piwnicki have also proposed another possible application of slow light [171], that of a slow light gyroscope. They show that using an optical gyroscope with slow light will increase its sensitivity by anything up to 8 orders of magnitude. Again the problem of observing EIT in solid materials makes this idea that is difficult to realise practically.

Further proposals for uses of slow light include those by Harris [172] in which slow light can be used in ballistic type experiments with atoms and ways in which slow light can be used for nonlinear interactions at very low light levels [173]. Other suggestions include those [174] in which slow light can be used in quantum entanglement experiments and experiments involving other fundamental quantum processes [175].

Slow light remains the most exciting development in the EIT world at the moment. Just over ten years after the original idea was proposed the idea of slow light has given the whole subject area of coherent light matter interactions a boost – asserting that new concepts are there to be found and new uses waiting to be made of them. In another ten years, who's to say, we may have optical black holes sitting in laboratories all over the world in much the same way that Bose-Einstein condensates have become the physics de jour.

1.5 Electromagnetically Induced Absorption

A related effect to EIT is that of electromagnetically induced absorption (EIA) which was first noted by Bergman *et al* [176] in an experiment in NO. However the phenomena has been most thoroughly investigated by a group from the Instituto de Physica in Montevidio, Uruguay [62, 177-179]. The effect can be observed in degenerate two level atoms and the Montevideo group has used rubidium in their experiments. The level structure investigated is shown in figure 1.17.

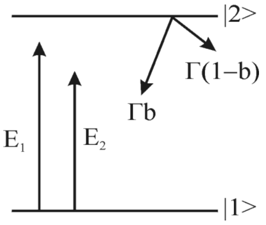

Figure 1.17: *Two level structure for observation of EIA. The two fields are a pump (coupling) and probe field. The parameter b is a branching ratio with b=1 corresponding to a closed transition. The value 1-b corresponds to the probability of level |2> decaying to a level other than |1>.*

Lezama *et al* have shown [62] that EIA can be observed in a degenerate two-level system provided that three conditions are satisfied: (i) That the F number of the ground state is one less that the F number of the excited state; (ii) the transition between the ground and excited state is closed and (iii) the ground state must be degenerate. They also show that the increase in absorption over that of a normal probe absorption trace can exceed 100%. Further, [179] the exact probe absorption spectrum that is observed is dependent on the field polarisations, the magnitude of any applied magnetic field (to lift the level degeneracy) and probe and pump field detunings.

In [177] Akulshin *et al* explain that analogous to the destructive interference effect found in EIT, it is a constructive interference effect that leads to EIA. In [62] Lezama *et al* expand this statement with a theoretical treatment that derives explicit density matrix equations for the degenerate two-level system. It is using this theory that allows the authors to produce the three conditions required for EIA. The underlying physical mechanism for EIA however remains unexplained. Results of a similar nature have also been present by Dancheva *et al* [180] although they too do not offer a explanation for the phenomena. A recent paper by Barreiro and co-workers [181], however, has proposed that the physical mechanism is the spontaneous transfer of light induced coherence from the excited state to the ground state. They show this by considering a four-level N-type system and generalise it to the experiment in [177]. They do not however show that their theory leads to the conditions for EIA outlined above. The assumption that EIA is a constructive interference effect in analogy to EIT remains sound, however.

The EIA effect can also be used to produce media with anomalous dispersion curves. Akulshin *et al* have shown [178] that negative dispersion can be observed which correspond to group velocities of –c/23000. They also noted that a negative dispersion can result in group velocities that are infinitely large (as can be seen by examination of equation 1.5). This they have recently reported [182] can lead to superluminal type effects [183, 184]. Such superluminal experiments have also been reported by Wang *et al* in a media using a Raman gain technique [185] to generate the anomalous dispersion. The possibility of achieving such effects via EIT will be briefly discussed in chapter 6.

1.6 ‘Old’ work on LWI and EIT

Recently a number of papers have been published on the Los Alamos pre-print server regarding LWI and EIT. Many of these are reprints of old Russian articles published in the late 1960s and early 1970s. These papers, many authored by A.K. Popov, purport to predict many of the effects that were later ‘discovered’ by Western scientists, for example inversionless lasing. These papers along with the references they contain are a reminder that many of the ideas now studied have been looked at in a different light in the past but that it perhaps takes a fresh flash of insight, such as that shown by Harris [23] to ignite research into a discipline. These papers will now probably only be of historical interest as the EIT/LWI community is unlikely refer to them very much. But they are given here as a nod towards completeness[1]. It is always interesting to note what research occurrs in Eastern Bloc countries that the West never gets to hear about.

1.7 Thesis Précis

The work in this thesis looks at a number of effects related to EIT. We begin, in chapter 2, with an overview of the theoretical models employed in the work found in subsequent chapters. Chapter 3 is primarily concerned with how mismatching the wavelengths of the probe and coupling fields affects both the EIT seen and the amount of inversionless gain that can be observed in the systems. Chapter 4 examines how moving beyond the standard model of EIT, in which we assume that all the laser fields are monochromatic, affects EIT and AWI in a V-scheme. Expressions for the observation of gain in such systems are derived.

The experimental work, in which the affect of changing the probe and coupling field polarisations is examined, begins in chapter 5. We find that EIT can be optimised by appropriately changing the relative polarisations. Chapter 6 looks at EIT in N-level schemes, in particular a four level cascade scheme. We introduce the idea of three photon EIT effects and also the possibility of controlling EIT by using a rf-field to couple two of the four levels as well as using the normal probe and coupling fields. This idea introduces the possibility of rf-controlled electromagnetically induced focussing. We also examine EIT in schemes with N levels and N-1 fields whereby ‘higher order’ EIT effects can be introduced, potentially by the application of rf fields. We see how EIT can be destroyed and recovered by moving to higher order level manifolds. Chapter 7 is an experimental treatment of some of the theory outlined in chapter 6.

In chapter 8 we examine the effect of not rf fields but microwave fields in EIT experiments, specifically the possibility of using a microwave coupling field. It is shown that microwave induced transparency although possible in atomic systems is exceptionally difficult and may be better achieved in molecular systems. Chapter 9 then details the development of an optical parametric oscillator (OPO) which could be used as the optical probe in a microwave induced transparency experiment. This OPO is also a novel device in its own right and we examine its properties and its potential.

The thesis concludes with chapter 10 and looks forward to work that may be carried out in the future.

The main thrust of this work has led to an examination of EIT in multi-level systems. This resulted from a study of how low frequency fields can be used to control optical fields in the context of EIT. Experimental work has been carried out that shows that rf fields can indeed manipulate optical fields via coherent processes. This work is, in context, rather timely. Now

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[1] These papers can be found at the Los Alamos preprint server: http://xxx.lanl.gov/. The specific papers are qu-ph/0005042, qu-ph/0005049, qu-ph/0005060, qu-ph/0005081, qu-ph/0005089, qu-ph/0005094, qu-ph/0005108, qu-ph/0005114 and qu-ph/0005118.

seen emerging in the literature is work which also looks at such multilevel systems. Lukin *et al* [162] have examined processes by which system dynamics can be 'engineered' in multilevel systems, Burkett *et al* [41] have also recently performed experiments investigating optical field effects in multilevel systems as have Gao *et al* [186] in the context of two photon inhibition (something investigated in chapter 5 and 6). The work of Wei and Manson, investigating EIT effects in multilevel systems within ESR transitions [72, 73] is also of relevance to this work.

To summarise the work as a whole, the effect of modifying the fields involved in EIT processes is examined. Examples of these changes include mismatching the wavelengths of the probe and coupling fields, introducing non-monochromatic fields, changing field polarisations or by the use of non-optical fields in EIT. The aim of this thesis is to investigate the role that each of these processes has on EIT in a number of atomic configurations.

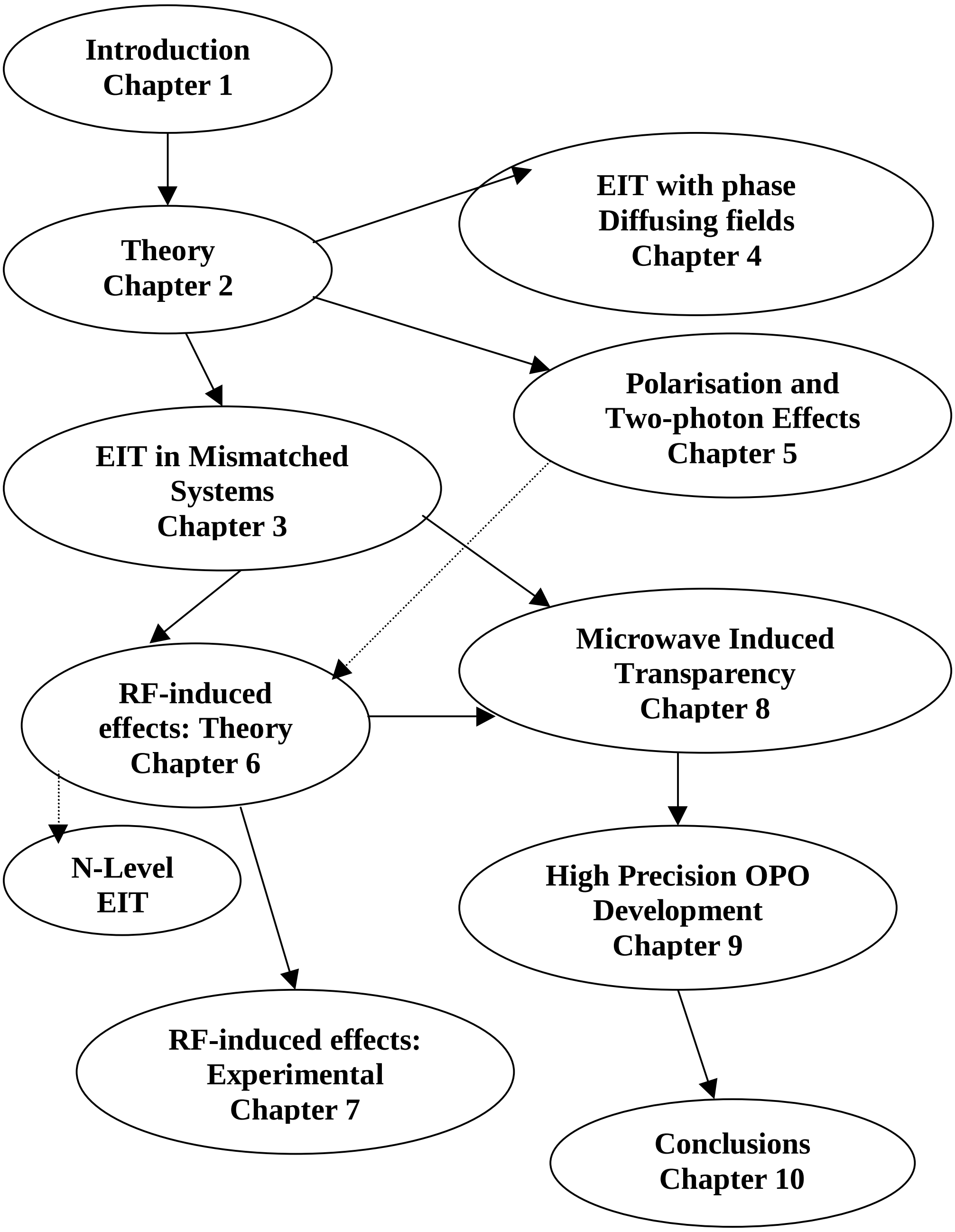

Figure 1.18: *Map outlining the structure of this thesis*

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