ATOM OPTICS

Optical isolation by hot atoms

A collection of hot rubidium atoms is shown to exhibit non-reciprocal optical transmission due to the interplay between thermal motion and electromagnetically induced transparency.

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Optical isolators, devices that allow the transmission of light in only one direction, play an important role in photonics by protecting lasers, amplifiers and other sensitive equipment from undesired reflections. However, their experimental realization is challenging, as it involves surpassing a fundamental principle in optics that dictates that signal transmission between two points in space is reciprocal and thus independent of the transmission direction. To date, the most common approach to break reciprocity is through the use of magneto-optics (the Faraday effect) and the use of certain magnetic materials that, when biased with a static magnetic field, provide a directionally dependent rotation of optical polarization.

However, the weak response of magnetic materials means that Faraday isolators are bulky devices that are not suitable for on-chip integration. For this reason, recent years have witnessed significant efforts in the development of non-reciprocal devices that do not rely on magnetism. In this context, different approaches have been explored, including spatiotemporal modulation of the refractive index[1], optomechanical effects[2] and chiral atoms[3].

Spatiotemporal modulation has been shown to work well at microwave frequencies, but it becomes more and more challenging to realize as the frequency is increased towards the optical regime. Devices that exploit optomechanics show promise for the design of non-reciprocal devices operating at optical frequencies, but typically require advanced nanofabrication techniques. Similarly, chiral atoms require sophisticated structures and operation at cryogenic temperatures.

Now, writing in *Nature Photonics*, Zhang et al. propose a technique for achieving strong optical isolation at around room temperature through a simple optical set-up based on components that are available in any optics laboratory[4]. The researchers' approach is based on electromagnetically induced transparency (EIT)[5] in optical cavities filled with hot atoms. High temperatures are usually considered detrimental for experiments involving EIT, since they lead to broadening of atomic energy levels and an increase of the optical loss. However, in contrast to this common belief, Zhang et al. show that when properly harnessed, high-temperature EIT can be advantageous when it comes to breaking reciprocity. In fact, the desired non-reciprocal response disappears when atoms are cooled down to cryogenic temperatures, defying the widely held view that lower temperatures result in better responses.

As it is commonly employed, EIT reduces the optical absorption of a probe optical signal as it propagates through a material when the material is subjected to another strong optical wave, usually referred to as the control signal[5]. A prototypical system where EIT is observed are atoms with a lambda-like configuration for their atomic energy levels, as shown in Fig. 1a. This is the case for the rubidium atoms used by Zhang et al. Without a control signal, atoms of this form exhibit strong absorption for a probe frequency $\omega_p = \omega_{21}$, where ω_{21} is the frequency difference between levels 1 and 2. On the other hand, in the presence of a control signal with a frequency $\omega_c = \omega_{32}$, where ω_{32} is the frequency difference between the energy levels 2 and 3, optical absorption is significantly reduced for the probe signal over a narrow window around ω_{21}. Importantly, the same phenomenon is observed even for a finite detuning $\Delta_c = \omega_c - \omega_{32}$, provided that ω_p is also detuned from ω_{21} by the same amount ($\Delta_p = \Delta_c$; Fig. 1a). It is this property that is central to the operation of the isolator proposed by Zhang et al.

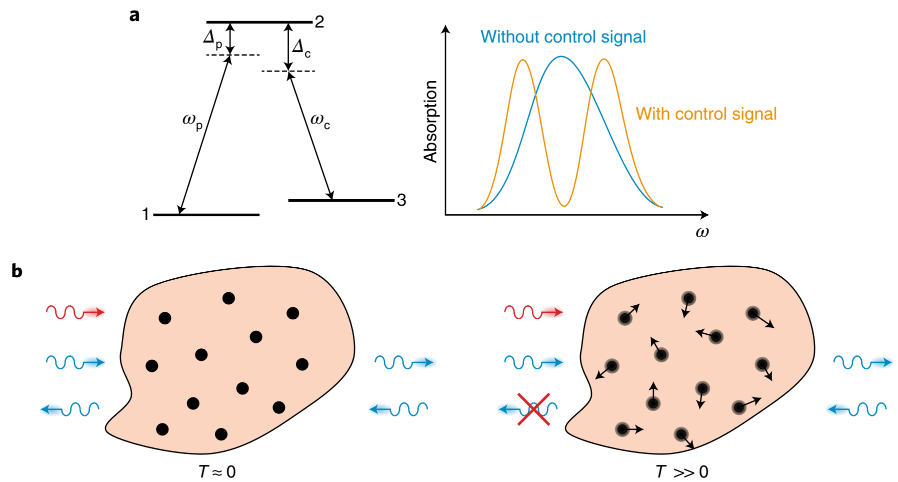

Fig. 1 | Optical non-reciprocity due to the interplay between EIT and thermal motion. **a**, Energy levels of an atom exhibiting EIT. EIT appears when the atom is illuminated with two optical waves, a weak one, called the probe wave with frequency ω_p, and a strong one, called the control wave with frequency ω_c. Δ_p and Δ_c are the detunings of the probe and control frequencies from ω_{21} and ω_{32}, respectively. EIT appears when $\Delta_p = \Delta_c$ (balanced detuning) and leads to absorption versus frequency for the probe wave as in the right panel. **b**, EIT directionality versus temperature, T, for a collection of atoms. The control signals, ω_c, are shown by red arrows and the incident and transmitted probe signals, ω_p, by blue arrows. At low temperatures, the atoms are stationary and EIT happens for both propagation directions for the probe signal (left). At high temperatures, the atoms experience thermal motion and EIT happens only for a probe signal propagating in the same direction as the control signal (right).

Electromagnetically induced transparency as described above is independent of the direction of the probe and control signals. After all, atoms are orders of magnitude smaller than optical wavelengths, and therefore the propagation direction of waves should matter very little for their response. Directionality comes into play when another phenomenon is considered, namely the tiny motion of atoms related to their thermal energy (Fig. 1b). Of course, this motion is random — at any time instant, different atoms move in different directions and the average velocity is zero, meaning that there is no directionality in the motion itself. However, the interplay between thermal motion with EIT can lead to a strongly directional response.

This unusual result is related to the Doppler effect for a moving atom. If v is the atom's velocity, the frequency ω of an incident wave is shifted by an amount $\Delta = -\omega v / c$ when we move from the laboratory frame to the moving frame of the atom. Here, c is the speed of light and v is positive or negative depending on whether the atom is moving in the same or the opposite direction to the incident wave. In other words, the atom perceives the wave as one with a frequency shift.

This fact has a dramatic effect on the EIT phenomenon, since it detunes the frequencies of the probe and control signals from the values required for EIT. Due to the randomness of the atomic motion, this detuning is also random and it generally leads to a significant degradation of the EIT effect. Yet, there is a case when this does not happen. As mentioned earlier, EIT persists for detuned signals, as long as the detuning is balanced, that is, $\Delta_p = \Delta_c$. For a moving atom, this condition is satisfied if the probe and control signals propagate in the same direction and have approximately the same frequency. This is the effect on which the isolator by Zhang et al. is based. For a probe wave propagating in the same direction as the control wave, the balanced condition for frequency detuning is satisfied for every thermally moving atom, leading to low absorption[6]. On the other hand, for counter-propagating probe and control waves, the system is completely detuned and there is no EIT effect. Therefore, signals are attenuated in the backward direction, with the amount of attenuation increasing as detuning increases. Since the detuning is proportional to the atom's velocity, isolation is expected to increase as the temperature increases. In reality, other phenomena, such as the gas density and energy level broadening, which also depend on temperature, determine the exact relation between non-reciprocity and temperature. Still, as was demonstrated by Zhang et al., at cryogenic temperatures, when thermal motion is largely suppressed, the non-reciprocal effect completely disappears, validating the mechanism described above.

The amount of non-reciprocity that can be attained after a single pass through the material is expected to be limited. For this reason, the researchers have embedded the EIT material into a cavity formed by four highly reflective mirrors. By controlling the transparency of the mirrors, one can effectively control the number of passes through the EIT material and in turn the transmission contrast in opposite directions.

The experiment of Zhang et al. was performed via a tabletop set-up at 55 °C, with a cavity formed by mirrors and a total length of 49 cm. One important question is whether the same effect can be obtained in miniaturized, ideally integrated systems, with a similar performance and at lower temperature. This will determine whether the proposed technique can be used for practical applications. Another important issue is the maximum power up to which this approach can work. The researchers' work is based on the assumption of a control signal significantly larger than the probe signal, which may pose an upper limit for the probe power, possibly preventing high-power applications. It would also be interesting to study the other extreme scenario of very weak probe signals, of the order of just a few photons, as is the case in quantum-information applications. The energy level broadening related to the microscopic Doppler effect may pose limitations in this case. These and other related questions are important to be addressed in future works, hopefully bringing this approach closer to practical applications. ❐

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VIEW FROM… OFS-26

Sensing new opportunities

Applications for optical fibre sensors have evolved beyond physical measurements in the defence, oil, gas and civil engineering sectors to tackle new opportunities in chemical detection.

Rachel Won

This year, the 26th International Conference on Optical Fibre Sensors (OFS-26) was hosted in the Swiss Tech Conference Centre at the École Polytechnique Fédérale de Lausanne (EPFL) campus in Switzerland from 24–28 September. The 2018 event attracted 538 attendees and 62 exhibitors from around the world, making it the largest to date with a total of 52 oral presentations and 312 poster presentations. Several novelties had been introduced to OFS-26 for the first time, such as double-blind reviewing, open access for all accepted papers, and a special session dedicated only to presentations from industry.

An interesting feature of the conference is that it is not 'owned' by any learned society or professional institution, but instead is organized by its own international steering committee. "The conference wants to keep its independence and to never compromise on the quality, complying with the strictest standards for the evaluation of submissions,"