is crucial for the suppression of loss, or amplification, of the signal.

The proposed approach can be compared to another loss-compensating technique explored in the context of NIMs, in which metamaterials are combined with gain media such as optically pumped doped polymers[6,7]. A significant advantage of the OPA approach is that it is not limited to the narrow wavelength range defined by the laser transitions of the laser gain media (for example, rhodamine 6G or quantum dots), and thus it can be made tunable in a wide frequency range.

Despite the exciting promise of the OPA approach to overcoming loss in a NIM, several fundamental and practical issues are still to be explored. On a fundamental level, the nonlinear optical response of nanostructured metamaterials is not completely understood or characterized, and cannot be predicted precisely. One of the major practical challenges is the realization of bulk nonlinear metamaterials. Other remaining issues include the development of approaches for realizing a controlled absorption coefficient at an idler frequency, which is essential for the proposed scheme; accounting for the pump depletion that is likely to take place in practice; and understanding the noise performance of the proposed device. Nevertheless, backward OPA is a promising route for providing robust transparency and amplification of light in highly absorbing NIMs, and not only has a strong potential to become a practical tool for loss mitigation in NIMs, but also highlights new physics enabled by the unique properties of metamaterials. ❐

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ATOMIC MEMORY

A little nonlinear help

Storing a light pulse in a vapour is by now a standard laboratory technique. For such optical memory to become truly practical, however, the fidelity of the technique has to be improved. Combining light storage with nonlinear wave mixing may offer a way forwards.

Michael Fleischhauer

An all-optical memory for light signals is a key ingredient for classical as well as quantum information technology, and several techniques have been developed for this purpose over the past few years. One promising approach is based on a phenomenon known as electromagnetically induced transparency (EIT), where the information carried by an incoming light pulse is transferred to an atomic spin transition by means of a control laser in a resonant Raman process. Although this technique has been demonstrated in vapours, its fidelity — that is, the extent to which original and retrieved pulses agree — is far too low for practical applications, such as quantum communication and information processing. A recent experiment by Ryan Camacho and colleagues from the University of Rochester and the California Institute of Technology, discussed on page 103 of this issue[1], suggests that a combination of nonlinear wave mixing and EIT light storage may help to solve this problem.

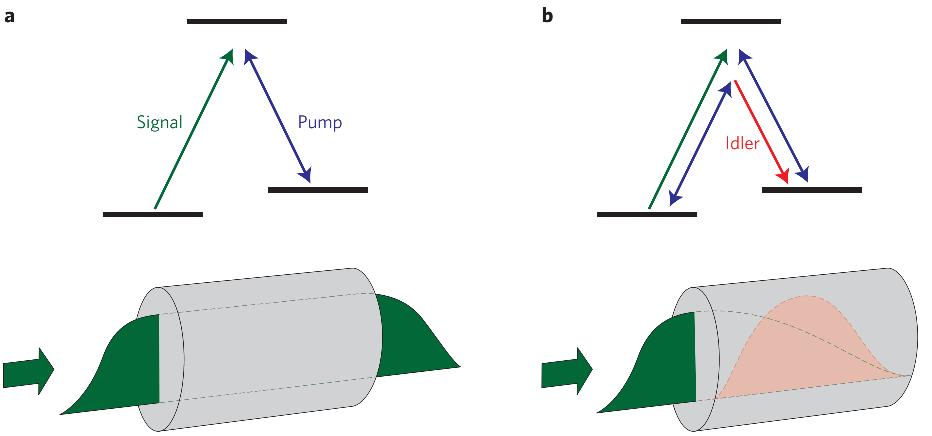

Figure 1 | Light storage assisted by electromagnetically induced transparency. **a**, Light storage in vapour cells can be achieved by means of EIT where a pump laser (blue) couples to a signal field (green) by a Raman transition to an atomic spin (top). However, the process is often limited by the impossibility of squeezing the entire signal pulse into the vapour cell (bottom). **b**, Camacho *et al.* have found an interesting method that may help to circumvent this problem. Light storage accompanied by the nonlinear generation of an additional idler field (red) leads to an effective additional compression, which enables the entire input pulse shape to be extracted upon retrieval.

One of the main challenges of this form of light storage is to capture the entire input light pulse so that it can be transferred to the atomic spin system. Because EIT is based on a resonant phenomenon, the bandwidth of EIT memory is limited to values of the order of the linewidth of the atomic transition, which is typically a couple of tens of megahertz and corresponds to a pulse duration in the microsecond regime. To be able to store such pulses, which are several hundred metres long, their entire length has to be squeezed into the storage medium in one go.

Scientists make use of a relatively simple trick to achieve this. The velocity of the light pulse inside the medium is many orders of magnitude smaller than in vacuum. As a consequence, the pulse is spatially compressed on entering the atomic ensemble: the front end, which is already inside the ensemble, moves with a low velocity, and the back end, which is still propagating at the speed of light in air, quickly catches up.

However, the possible compression, given by the ratio of the two pulse velocities, is limited by the 'optical depth' of the medium, which is proportional to the density of the atoms in the storage medium as well as the strength of the coupling between the atoms and the optical probe field used. In vapour cells, researchers have to make sure that the atomic density (and therefore optical depth) does not become too large as this can compromise the quality of the retrieved pulse, owing to the increased influence of decoherence processes. To achieve the best possible fidelity for a limited optical depth, special optimization strategies[2] have to be used, and even then it is not possible to approach the desired fidelity.

In a typical EIT scheme, two coherent optical fields — a probe (signal) pulse and a much stronger coupling (control or pump) laser — are tuned to interact with three quantum levels of a material. They couple to different 'legs' of a so-called lambda-type configuration of atomic transitions (represented in Fig. 1a). The probe pulse is tuned near resonance between two of the states, and the pump pulse is tuned near the resonance of a different transition. If the states are chosen carefully, the presence of the pump field creates a transparent spectral window that can be detected by the probe.

Camacho *et al.* pursue a different approach (Fig. 1b). In their scheme, the pump laser also couples to the probe-field transition. In this way a fourth field, called the idler, is coherently generated, and the process is termed resonant four-wave mixing. Because all fields propagate in the same direction, the interaction of the idler field with the three-level medium modifies the signal field. As a result, a combined signal–idler mode builds up and evolves in the medium (Fig. 1b). The authors' experiment demonstrates that it is possible both to read and to write using four-wave mixing and two lambda resonances simultaneously, and hence record information about the input signal and generated idler waveforms for later retrieval. Remarkably, the nonlinear mixing amplifies the effective compression of the combined field mode.

After sending a probe pulse a few microseconds long into a hot rubidium vapour and switching off the control laser, Camacho and colleagues store the generated signal–idler mode in the ground-state spin transitions of the atomic ensemble for up to several hundred microseconds. Switching on the control laser after the storage period then leads to a regeneration of the signal and idler pulses. As expected, the peak amplitude of the retrieved light pulses decreases exponentially with the length of the storage time, owing to the finite lifetime of the atomic spin coherence. Surprisingly, however, the results show that the form of the retrieved pulse exactly matches that of the input pulse, proving that the information imprinted in the input pulse shape is restored.

To verify that the shape of the retrieved pulse is indeed determined by the input beam and is not the result of pure coincidence, the authors perform a storage of partial input waveforms. They switch off the control laser once different parts of the input pulse have already passed the vapour cell. By piecing together the front end of the pulse, which is not stored, and the back end of the pulse, which is stored and retrieved after a time delay of 10 μs, Camacho *et al.* are able to reproduce the entire input pulse shape very nicely.

Owing to the unavoidable amplification noise in the four-wave mixing process, the proposed technique may be of limited use for quantum information purposes. Nevertheless, the experiment opens an interesting new avenue in the quest for a high-fidelity, all-optical memory for light. ❐

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SILICON PHOTONICS

A chip-scale one-way valve for light

For integrated photonics to take off, light signals zooming around optical chips must be successfully isolated from one another. Scientists at Stanford University have now designed a miniature one-way valve for light that uses photonic transitions and is potentially compatible with silicon-chip CMOS fabrication processes.

S. J. Ben Yoo

Being able to isolate optical signals on-chip is a great challenge for integrated photonics, and is crucial to the success of large-scale photonic integrated circuits. Photonic integration has the potential to reduce power consumption, size and cost while improving reliability and performance. Moreover, integration of photonic components on a silicon CMOS-compatible platform brings additional scalability and functionality as a result of the experience of the vast electronics industry. However, cross-talk and interference in photonic and electronic integrated circuits ultimately limits the scalability of integration. On page 91 of this issue, Zongfu Yu and Shanhui Fan of Stanford University propose a way of achieving broadband, non-reciprocal optical isolation in a waveguide structure that is compatible with silicon CMOS-integrated photonics[1].

As yet, the techniques that have been used to achieve on-chip optical signal isolation have relied on materials or processes that are not fundamentally compatible with silicon CMOS processes. Non-reciprocal optical isolation, which requires time-reversal symmetry breaking, is typically achieved using bulk components made from materials that show magneto-optical effects, which are incompatible with integrated photonics. Recent efforts to achieve optical isolation in integrated photonics systems have involved waveguides with magneto-optical materials bonded to or incorporated into the waveguide. Optical isolation has also been attempted using chiral structures (reciprocal structures with no inversion symmetry), but this is only successful for specific optical modes of reflected waves. Nonlinear optical processes or electro-absorptive modulators can be effective, but optical isolation occurs only at specific power ranges, or with associated modulation sidebands.

Yu and Fan propose an unusual solution to the problem of isolation that is based on the effects of photonic transitions. Using a dynamic refractive index modulation,