Unexpected weak interaction

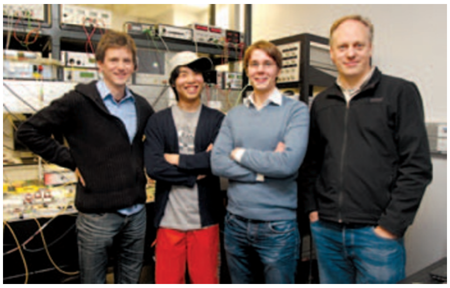
Stéphane Coen and Miro Erkintalo from the University of Auckland in New Zealand talk to *Nature Photonics* about their surprising findings regarding a weak long-range interaction they serendipitously stumbled upon while researching temporal cavity solitons.

What is your work about?

Temporal cavity solitons are dissipative solitons that form in passively driven nonlinear resonators. They can persist for as long as the continuous-wave driving beam is applied. We discovered that in optical fibre cavities these solitons can interact via sound waves and that these interactions are orders of magnitude weaker than any that have been witnessed so far in either conservative or dissipative systems. In the weakest case we observed, temporal cavity solitons needed to propagate more than an astronomical unit (149,597,871 km) for their separation to change by a mere 20 cm or so — this corresponds to a 12-order-of-magnitude difference in scale. These results are compounded by the long-range nature of the interactions. Indeed, the solitons are localized within 400 μm (equivalent to about 2 ps), but they interact even when they are separated by metres (about 20 ns). Our experiment also reveals that solitons are robust enough for such weak interactions to accumulate coherently over hundreds of millions of soliton lengths. Some of our measurements revealed that two temporal cavity solitons change their relative separation by half an attosecond per soliton period. Such a displacement corresponds to 1/10,000 of the soliton carrier wavelength. Naively, one would expect that such a minute change in the carrier wave underlying the envelope would be insignificant and easily swamped by noise and perturbations. However, the tiny effect induced by the acoustic interactions eventually accumulates, giving rise to measurable effects after propagation over millions of kilometres.

How did you discover this interaction?

It all came as a complete surprise. We did not initially aim to observe ultraweak soliton interactions or figure out how we could do that. We originally wanted to explore the use of temporal cavity solitons in telecommunication applications. However, after setting up the experiment, it quickly became evident that the pulses were, unexpectedly, very slowly attracting and repelling each other over a very long range. We expected short-range interactions as they are well documented in theoretical studies, but the long-range nature of the interactions was quite puzzling. At first, we thought that they were caused by some spurious effects and tried hard to eliminate them, but to no avail. Hilariously, these interactions were actually preventing us from performing some of our planned research! As they could not be accounted for by the basic model of temporal cavity solitons, which includes the instantaneous Kerr nonlinearity, chromatic dispersion and cavity losses, some physics was clearly missing. We then had the brilliant idea of searching on Google for long-range soliton interactions — if ever there was a stroke of genius, that was it! Acoustic interactions mediated by electrostriction quickly came to the surface. We then verified that what we were observing was compatible with this process.



ANNA YANG

Stéphane Coen, Jae Jang, Miro Erkintalo and Stuart Murdoch (left to right) believe their findings are potentially applicable to the whole of nonlinear science, not just photonics, as solitons constitute the fundamental building blocks of descriptions of nonlinear wave phenomena.

What distinguishes your work from previous studies?

Both short- and long-range interactions produced by various mechanisms had previously been observed. In particular, Kerr solitons interacting in optical fibres through sound waves were studied in the 1990s in the context of optical telecommunications. The critical difference is that, in our case, temporal cavity solitons appear to interact much more weakly than in any previously reported observation of more traditional solitons. There are two key aspects of our work. First, the solitons circulate in a loop. Hence, we could monitor soliton interactions over indefinitely large propagation distances; unlike in many other experiments, we were not limited by fibre length or the size of a nonlinear crystal. Second, temporal cavity solitons are attractors and are strongly tied to the external driving beam of the passive resonator. This actually severely restricts the extent to which their group velocities can vary and explains the very weak nature of their interactions.

What are the implications of this work?

Similar acoustic effects may play a role in whispering-gallery-mode Kerr microresonators in which broadband frequency comb generation has been demonstrated under continuous-wave excitation. These experiments are conceptually the same as our fibre ring experiment, but are on a much smaller scale. It is now thought that temporal cavity solitons may be spontaneously excited in microresonators; they may well correspond to the temporal structures underlying the generated frequency combs — a cavity soliton leaving the cavity at each round trip forms a periodic temporal signal, which must be associated with a frequency comb in Fourier space. As cavity solitons are involved and the materials are similar, sound waves may similarly be excited in microresonators and affect the comb dynamics.

What future plans do you have?

The interaction of temporal cavity solitons over long distances is actually a problem for their envisioned application as bits in an all-optical buffer. However, this problem can be easily circumvented by modulating the driving beam, which would create potential wells in which the solitons would be trapped — we are working on this as we speak. One limitation of the present study is the slightly inaccurate prediction of the stable separation between two cavity solitons, which indicates that the transverse acoustic model of optical fibres is somewhat incomplete. We considered various corrections, but none of them seems to explain the observed differences. This needs further investigation.

INTERVIEW BY RACHEL WON