Atoms in a spin

The miniaturization of laser-based atomic magnetometers could be used in neuroscience to investigate the inner workings of the brain. *Nature Photonics* spoke to John Kitching at the National Institute of Standards and Technology about the latest developments.

What are the underlying principles of atomic magnetometers?
Atomic magnetometers are based on the precession of atomic spins in a magnetic field. Using lasers it is possible to first orient the spins along some direction, and then measure how this orientation is altered by the magnetic field.

The key idea behind your work is miniaturization. Is measuring changes in small vapour cells difficult?
Many atomic magnetometers use an orthogonal pump–probe scheme — one laser, the pump, polarizes the atoms in some direction, and then a probe laser, propagating perpendicular to the pump, measures how the polarization of those atoms changes when a magnetic field is applied. The atoms are housed in alkali vapour cells and arranging access for both the pump and probe beams in small cells is difficult. To get around the problem, my colleague Vishal Shah came up with the idea of using a single laser beam. The basic technique is in fact similar to that used in some of the first atomic magnetometers developed in the 1960s. In the absence of a magnetic field, when a circularly polarized laser beam is passed through an atomic vapour, the atoms absorb angular momentum and eventually become polarized so that they can no longer absorb light and the optical transmission through the cell is at a maximum. Now, if you apply a magnetic field that is perpendicular to the laser-beam direction, the atoms see the field and they try to precess; as their orientation changes they start to absorb more light. The change in transmission is related to the size of the magnetic field. With this technique, our very small devices achieve a sensitivity below 70 fT $\mathrm{Hz}^{-1/2}$.

Mini magnetometry. John Kitching uses the optical properties of atomic vapours to sensitively measure weak magnetic fields.

How do you make your instruments so small?
Until a few years ago, essentially all alkali vapour cells were made using glass-blowing techniques: you take a glass tube and heat it up to fuse windows on the side and then fill it with alkali atoms using a vacuum system. This process is expensive, time-consuming and generally results in fairly large cells. Our process is based on micromachining, similar to that used in the semiconductor industry. Starting with a silicon wafer, we lithographically define a 1-mm^2 square and, using chemical etching, we make a hole through the wafer. The silicon is about a 1 mm thick, so this hole is 1 mm^3 in volume. We then bond glass onto one surface of the wafer and place the whole thing in a vacuum system. Here we can introduce the alkali atoms and bond a second glass surface to seal the cell closed.

The advantage of this fabrication process is that, not only can you make cells that are very small, but it's a very scalable process: you can easily go from 1 mm down to 100 µm. Another really powerful aspect of this technique is that you can make many cells on the same wafer. We are hoping that this process will lead to a much reduced cost for these types of instruments.

How do your devices compare to other approaches to sensitive magnetometry?
For many years the gold standard has been set by superconducting quantum interference devices, or SQUIDs. These achieve sensitivities of around 1 fT $\mathrm{Hz}^{-1/2}$. They are exceptionally sensitive; however, the problem is that you need a cryostat because the best ones must be cooled down to 4 K, making them cumbersome, expensive and difficult to use. In 2003, it was shown by Mike Romalis and his colleagues at Princeton University that using the so-called spin-exchange-relaxation-free technique, atomic magnetometers could achieve sub-1-fT $\mathrm{Hz}^{-1/2}$ sensitivity. This was a great breakthrough because it demonstrated that atomic magnetometers could achieve sensitivities better than SQUIDs. So what I think our work shows is that you can approach the sensitivities of SQUID sensors but in very small packages and without the need for cryogenics.

Why is there a need to make such tiny magnetometers?
A hot field within neuroscience right now is magnetoencephalography or MEG — a magnetic sensor is placed near the brain to measure the magnetic field. Generally, an array of sensors that goes all the way around the head is required — difficult to achieve with large magnetometers. Our small sensors can be very precisely placed, enabling very good resolution of the localized magnetic activity in the brain. On a similar theme, we have already done preliminary tests with colleagues at the University of Pittsburgh measuring the magnetic fields produced by the heart of a mouse, so-called magnetocardiography.

What sensitivity is likely to be required for a practical instrument?
One of the main brain activities is the alpha wave. These produce signals that are about 1 pT just outside the skull at about 10 Hz. So the sensors we have now could measure this, but with a poor signal-to-noise ratio; we probably need to improve the sensitivity by a factor of about five or ten. But this is really a first attempt, and I think we will get down to 10 fT $\mathrm{Hz}^{-1/2}$ with further optimization.

Interview by David Gevaux.

John Kitching and his co-workers have a letter on atomic magnetometers on p649 of this issue.