Optical Microchip Detection of Nuclear Magnetic Resonance

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Abstract: We demonstrate optical detection of nuclear magnetic resonance on a microchip. A theoretical optimization indicates detection limits that are competitive with that demonstrated by microcoils in high magnetic fields, without requiring superconducting magnets.

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In conjunction with a resonant paramagnetic atomic vapor (typically an alkali), light can be used to efficiently detect small magnetic fields [1]. Recent advances in optical-atomic magnetometery [2] have enabled the development of sensors rivaling or even surpassing the magnetometric sensitivity of superconducting quantum interference devices (SQUIDs), without requiring the use of cryogenics. By placing such a sensor in close proximity to a polarized sample of nuclei, one forms the basis for optical detection of nuclear magnetic resonance (NMR).

In this paper, we present a novel method for optical detection of NMR that incorporates several recent advances in the fields of microfabrication and optical-atomic magnetometry [3]. Information about nuclear spin precession of a polarized fluid is encoded remotely [4] and then the fluid flows from the encoding region into a microchip sensor. The microchip sensor, with dimensions of approximately 1 cm, consists of an alkali vapor cell and microfluidic channel, fabricated using lithographic patterning and etching techniques. A schematic of the experimental setup used in this work is shown in the left side of Fig. 1. The right side of Fig. 1 shows an example of a remotely detected, phase encoded free induction decay of water.

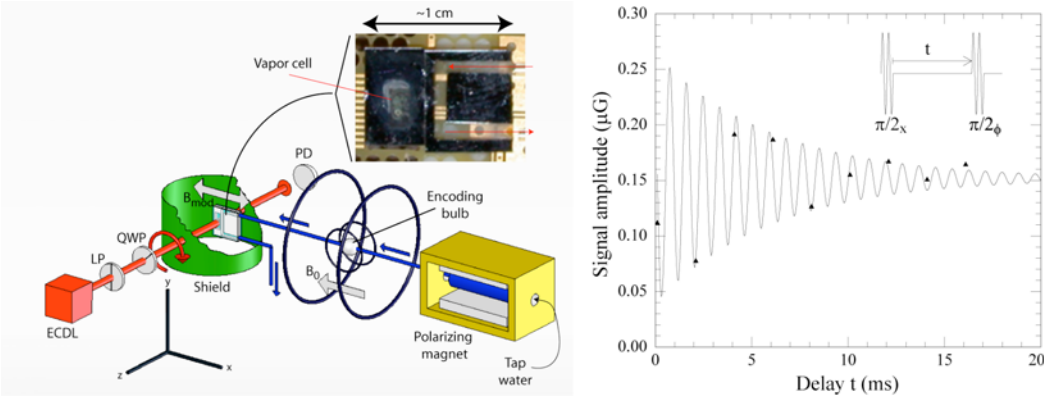

Figure 1 (Left) Schematic of the experimental setup. Water is polarized in a 7-kG magnetic field, flows into an encoding region where audio frequency magnetic field pulses are applied and then into the optical microchip where the longitudinal component of the magnetization is detected. ECDL: external cavity diode laser, LP: linear polarizer, QWP: quarter wave plate, PD: photodiode. (Right) Phase encoded, remotely detected free induction decay (triangles). The solid line is a fit to a numerical model which includes the effects of finite duration pulses and counter-rotating components of the applied AF field, resulting in T_2=6 ms. Inset shows the phase encoding sequence.

We have realized pulsed NMR linewidths of about 26 Hz, limited, we suspect, by flow dispersion and residence time in the encoding region. For a fully optimized system, with 1-mm^3 vapor cell and fluid

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detection volumes, we estimate that the magnetic field from $7x10^{13}$ protons, polarized in a 1-Tesla magnetic field (easily generated by permanent magnets) can be detected with a signal-to-noise ratio of about 3 in 1 second of integration. This level of sensitivity is competitive with that demonstrated by microcoils in high magnetic fields, without requiring the use of superconducting magnets.

The magnetometer uses a single laser beam to pump and probe alkali spin precession [5], facilitating wafer level construction of integrated devices. The magnetometer and fluid detection volume operate at zero magnetic field which has several advantages over magnetometers operating at high magnetic field. First, when precession of the alkali vapor in the magnetic field is small compared to the spin-exchange rate, as in the present work, relaxation due to spin-exchange collisions can be completely eliminated, the so-called SERF (spin-exchange relaxation-free) regime [2]. The dominant relaxation mechanism in this case is then spin-destruction collisions, which have cross sections 2-3 orders of magnitude smaller than that of spin-exchange collisions, allowing small magnetometers to achieve higher sensitivity. Second, in order to couple efficiently to the nuclei in the sample, the magnetic resonance frequencies of the alkali atoms and the nuclei must be matched. Due to the dramatic difference in the gyromagnetic ratio of the alkali atoms and the nuclei, the only place at which this can occur is at zero magnetic field. This eliminates the need for a piercing solenoid to create a leading field, which increases the proximity of the sensor and sample and removes noise associated with imperfections in the solenoid.

In the technique described here, information about spin-evolution is mapped onto the longitudinal component of the magnetization, which is subsequently detected by the atomic magnetometer. This is in contrast to conventional inductive detection of NMR which is sensitive to the transverse component of the magnetization. This results in an improved duty cycle by a factor of T_1/T_2 compared to conventional inductive detection of NMR, when integrating for times long compared to T_1.

In conclusion, we have demonstrated a novel marriage of recent advances in the fields of optical-atomic magnetometry and microfabrication that allow the optical detection of remotely encoded NMR. In principle, it should be possible to achieve sensitivities competitive with that demonstrated by microcoils in large magnetic fields, without requiring the use of superconducting magnets or cryogenics. Hence the technique presented in this paper presents a promising alternative to NMR of mass-limited samples, important, for example, in the fields of drug screening and development. Progress on detection of J coupling, chemical shifts and multidimensional NMR spectroscopy will be reported.

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