Microfabricated Optically-Pumped Magnetometers

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Abstract: The miniaturization of atomic devices with methods lent from microelectromechanical systems (MEMS) has enabled small, low-power high-performance sensors. Pioneered by the development of the chip-scale atomic clock, the technology has advanced to gyroscopes and optically-pumped magnetometers. At the heart of each device is a MEMS alkali vapor cell. It is integrated with micro-optical components, heaters, photodiodes, and lasers in a miniature package of less than 1cm^3. MEMS fabrication can open the door for low-cost fabrication in large quantities and make atomic sensors manufacturable with lithographically-defined precision.

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1. Introduction

Laser spectroscopy is a powerful tool to measure frequencies of atomic transitions with very high precision and accuracy and has made the second the best realized unit in the International System of Units [1]. Several high-precision sensors also take advantage of this high precision and long-term stability, such as gyroscopes [2], accelerometers [3], gravimeters [4], and magnetometers [5]. The high performance of these devices often comes at the expense of large and complicated systems with high power requirements. In order to bring atomic sensors to a broad user community in large volumes at reasonable cost, microfabrication can play a central role. It does not just make the sensors smaller, but also reduces their power consumptions to a range, suitable for operation with small batteries. It adds lithographically defined precision and the possibility for parallel fabrication at the wafer scale.

2. MEMS vapor cells

Atomic MEMS sensors were enabled by the technological advancement of MEMS alkali vapor cells. They confine the atoms inside bulk-micromachined silicon cavities under the atmosphere of a buffer gas. Several methods have been developed to transfer the atoms into the silicon cavities, such as direct deposition [6], thermal evaporation [7], and thermal [8], or UV dissociation [9], just to name a few. The cells are then closed by anodically bonding a glass window to the cavity and dicing the wafer chip into individual dies. MEMS cells have been made with a variety of alkali atoms and buffer gasses. Since the lateral shapes are defined by the lithography, many different sizes and shapes have been made. Cell sizes currently range from several hundreds of microns to several millimeters.

3. Progress of microfabricated optically-pumped magnetometers

We have developed several microfabricated magnetometers over the past 8 years. A summary of the noise-equivalent magnetic fields as a function of frequency for several devices is shown in Fig. 1 on the left. The first device in 2004 was based on a coherent-population trapping resonance on the hyperfine ground-state transition of Rb [10]. A photograph of the integrated physics package is show in Fig. 1 on the right. It consisted of a vertical-cavity-surface emitting laser, micro-optics, heaters, a vapor cell, and a photodiode. The volume of the physics package was only 10 mm^3, and it reached a noise equivalent magnetic field around 40 pT/Hz$^{1/2}$. The performance of MEMS optically-pumped magnetometers was improved by nearly one order of magnitude in 2006, by interrogating a Zeeman transition instead, while the overall layout of the physics package remained very similar [11].

A big improvement in sensitivity is possible, when operating at low magnetic fields and high atomic densities due to the suppression of spin-exchange collisions [12]. Our single-beam MEMS magnetometers operating in that regime achieve noise equivalent magnetic fields around 20 fT/Hz$^{1/2}$. The devices consist of arrays of sensor heads coupled to a control system by an optical fiber [13]. The cells were optically heated and suspended inside a vacuum enclosure. The best performance of 5 fT/Hz$^{1/2}$ was achieved in a tabletop system with a microfabricated vapor cell [14]. This noise level is very close to those of commercially-available low-temperature superconducting quantum interference devices (SQUIDs).

Small low-power magnetometers are of interest for applications such as geophysics, magnetic anomaly detection, surveillance, or space. The scalar nature makes optically-pumped magnetometers in the precession mode unique among magnetic field sensors and attractive for operation of moving platforms. On the other hand, due to their high magnetic field sensitivity, MEMS zero-field magnetometers have been used in biomagnetic applications requiring high performance, such as nuclear magnetic resonance [15], magnetocardiography [16], magnetoencephalography [17], and magnetic nanoparticle relaxometry [16].

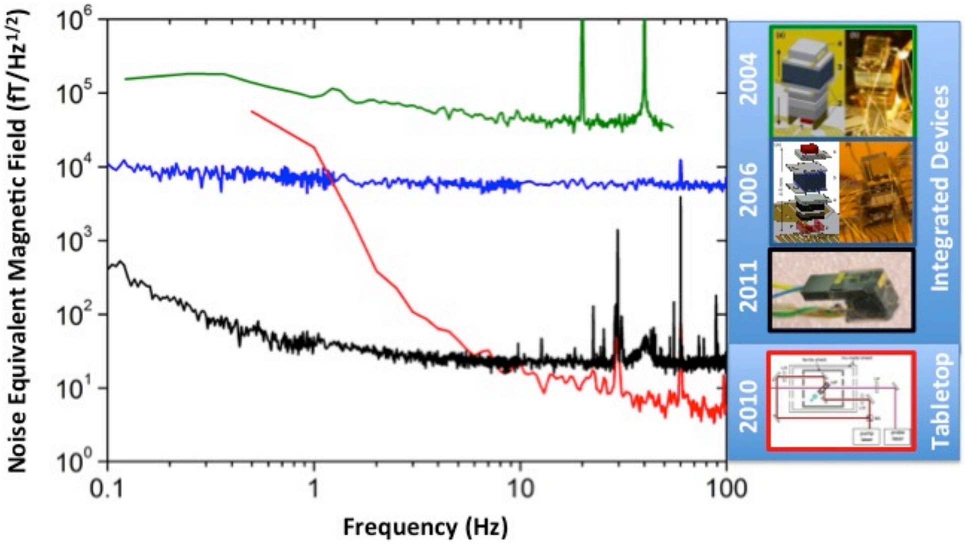

Fig. 1. Noise equivalent magnetic field as a function of frequency for various MEMS magnetometers developed by us. The panel on the right shows photos of three different devices, while the last performance (red) was measured in a tabletop experiment with a MEMS cell. (Green: 2004, blue: 2006, black: 2011, red: 2010).

4. References

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