A microfabricated photonic magnetometer

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***Abstract*—An integrated optically-controlled sensor, suitable for remote, high-sensitivity detection of magnetic fields is presented. The sensor head is free of electrical currents or metal parts, which largely eliminates any spurious fields created by the sensor itself. We demonstrate the operation of the sensor in a scheme first published by Bell and Bloom [1] and reach a sensitivity of 2.6 pT/Hz$^{1/2}$ at 30 Hz, limited primarily by the photon shot noise of the detector.**

I. INTRODUCTION

Atomic vapor magnetometers have been widely used over the past 50 years in fields that range from mineral and oil exploration [2] to unexploded ordinance detection [3] and biomedical applications [4]. However, in many applications the size or the power consumption of the device limit or inhibit the use, for example remote sensing or space applications [5]. Recent developments have shown improvements in miniaturization as well as reduction in overall power needed by utilizing microelectromechanical systems (MEMS) technology, while maintaining sensitivities of a few pT/Hz$^{1/2}$ [6]. Sensors based on chip-scale atomic magnetometers have been demonstrated and allow both high sensitivity and low cost in a small, integrated device. This so called “physics package” includes the vapor cell, the probing laser, electric heaters, a detector, and optics in one integrated stack. While all components can be combined in a very small volume (typically 12 mm^3) [7], there are benefits to separating the magnetically sensitive volume from the rest of the magnetometer. Heating and laser currents as well as magnetically susceptible materials near the vapor cell distort the signal and usually need to be accounted for. When individual sensors create fields of their own, closely spaced arrays of multiple sensors are difficult to realize since the electrical currents not only influence the originating sensor but the neighboring ones as well. In previous setups the heating current was modulated and measurements of the magnetic field only taken during the off-cycle, therefore not allowing a continuous data flow [6]. In this paper we demonstrate a photonic sensor, where the vapor cell is heated by absorption of laser light and the magnetic signal is detected in an all-optical way. Furthermore, by simplifying the sensor head an easy and cost-effective assembly is possible that could potentially lead to an even smaller detector design.

II. MAGNETOMETER PRINCIPLE

In the atomic magnetometer presented here, external magnetic fields cause a precession of the atomic spin. The precession (or Larmor) frequency is directly proportional to the magnetic field and expressed as $B = \nu_L/\gamma$, where ν_L is the Larmor frequency and γ the gyromagnetic ratio (γ = 7 Hz/nT for ^{87}Rb). A laser (λ = 795 nm) is used to probe the D1-line of the rubidium vapor. By modulating the laser at the Larmor frequency ν_L of the magnetic field, a precession of the atomic spins is excited [1]. The transmitted light is monitored to detect the resonant behavior of the atomic precession with phase-sensitive detection. In this way, the same light can be used for pumping the atoms, as well as probing them [Fig. 1].

III. DEVICE DESIGN

For an all-optical sensor head, the pumping and probing of the atoms and the heating of the vapor cell to its operating temperature are both done with laser light, which is sent to the vapor cell through optical fibers. The light to pump/probe the ^{87}Rb vapor is circularly polarized to polarize the atoms. The vapor cell has to be heated to 80 - 120 °C to raise the internal vapor pressure, and therefore rubidium density, so that about 30 % of the light is absorbed. The cell is heated with a one Watt, high power diode laser (λ = 915 nm) coupled into a multimode fiber and directed onto one of the walls of the cell where it is absorbed. Depending on the size and thermal isolation of the cell, temperatures exceeding 150 °C can easily be achieved [8].

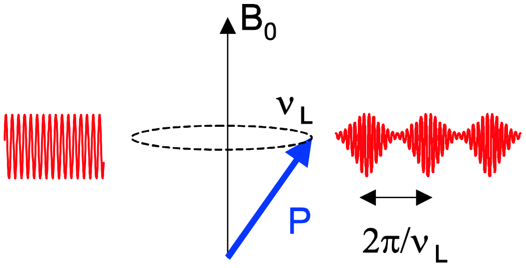

Figure 1. Atomic magnetometer principle

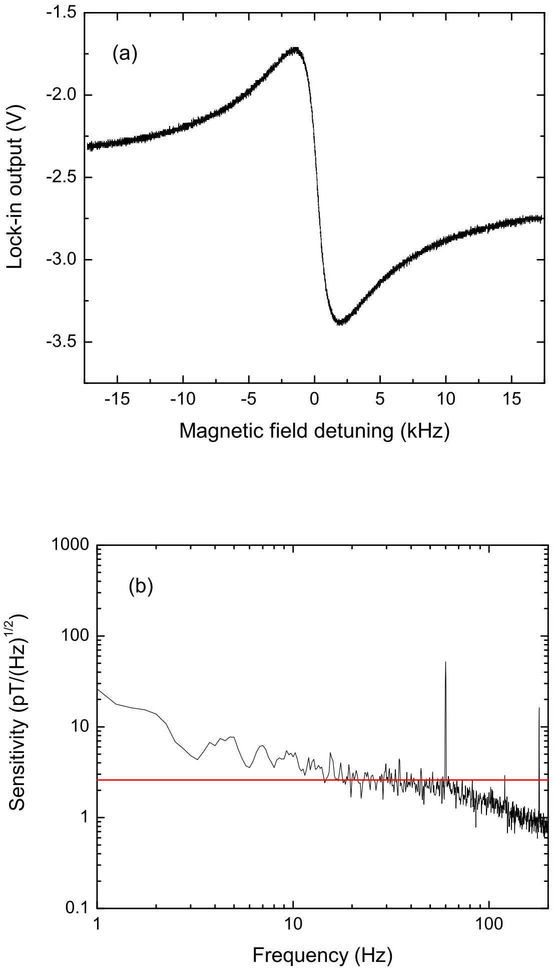

Figure 2. (a) Magnetic resonance and (b) magnetometer sensitivity at 50 kHz Larmor frequency

In case of the probing light the linearly polarized output of a vertical-cavitiy surface-emitting laser (VCSEL) is focused into a single mode, polarization-maintaining fiber and converted into circularly polarized light before entering the vapor cell by use of a quarter-wave-plate. The transmitted light is collected by a 400 µm diameter multimode fiber in close proximity of the vapor cell and delivered to a silicon photodiode. Due to the small numerical aperture of the emitting single mode fiber almost all of the transmitted light is collected behind the vapor cell.

The sensor head is made of a stack of five 1 mm thick silicon layers individually etched with deep reactive ion etching (DRIE), which are glued together to form the housing for the rubidium cell and the optics, and provide attachment for all optical fibers [Fig. 3]. The folding design of the optical beam path allows all fibers to be attached to one side of the device and the vapor cell is suspended inside the silicon stack by eight 400 µm wide polyimide tethers providing thermal isolation and mechanical rigidity.

The heart of the magnetometer is a MEMS-based rubidium vapor cell, described elsewhere [8], which is comprised of a 1 mm thick silicon layer with a 1 mm^2 etched hole and borosilicate glass windows anodically bonded to each side of the silicon. The cavity is filled with ^{87}Rb atoms in a nitrogen atmosphere. The nitrogen acts as a buffer gas to minimize collisions of the rubidium atoms with the cell walls.

The sensitivity of an atomic magnetometer depends on the density of the rubidium vapor and the intensity of the probing light. The atom density is controlled by the cell temperature. If the rubidium density is too high, Rb-Rb collisions will increase, which in turn leads to increased spin relaxation. If the vapor is too cold, not enough atoms are available for probing, resulting in a decrease of the signal-to-noise ratio. We found the best sensitivity occurs at a temperature of 97 °C, corresponding to an absorption of about 20 %. To achieve a 97 °C operating temperature, 200 mW of optical power is delivered to one of the silicon cell walls. Thermal gradients throughout the cell are not of concern since silicon has a good thermal conductivity of 149 W/m·K. Experiments show a line width comparable to more uniformly heated cells, suggesting little or no broadening of the magnetic resonance due to temperature differences throughout the cell volume. A reduction in power consumption is possible by evacuating the sensor head and increasing the optical absorption on the cell wall for more efficient heating.

When the device is evacuated, the heat loss is dominated by radiative heat transfer and conduction through the polyimide suspension. Assuming black-body radiation for the vapor cell, we estimate that 23 mW are dissipated at

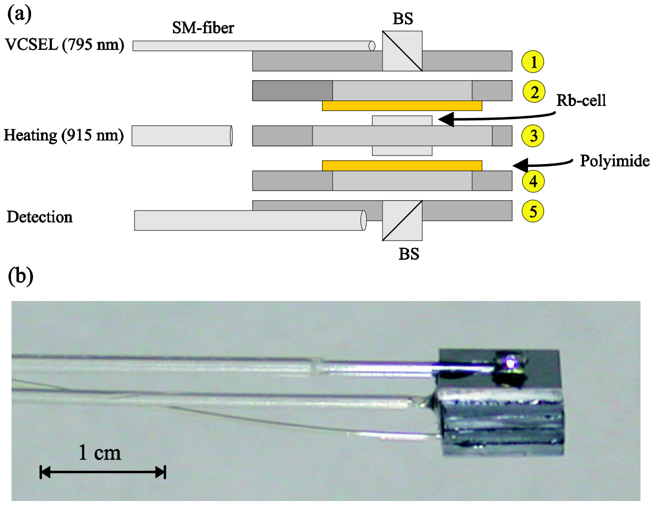

Figure 3. (a) Five layer structure of cell assembly: 1. Incoming probing light, directed downwards with beamsplitter, 2. upper polyimide suspension, 3. heating fiber and ^{87}Rb cell, 4. lower polyimide suspension, 5. collection path, (b) Assembled sensor head with optical fiber leads.

97 °C. The conduction of the polyimide tethers account for about 1 mW. With silicon reflecting 30 % of the heating light at normal incident, an absorptive coating on the cell wall can increase the heating efficiency by similar amounts. It is likely that the overall power needed for heating can therefore be reduced to less than 20 mW.

An external magnetic field of 7 μT is applied perpendicular to the pump light. Figure 2a shows the resonance when a modulation frequency of 50 kHz was applied to the laser and the magnetic field swept by 4 μT. The resonance width of 1 kHz determines the bandwidth of the magnetometer. The sensitivity reached with this configuration can be seen in figure 2b. It shows a value of 2.6 $pT/Hz^{1/2}$ at 30 Hz, an improvement of a factor of 2 over previous results [6].

IV. CONCLUSION

We have demonstrated a magnetometer with a sensor head that is connected and operated entirely through optical fibers. This all-optical approach implies several advantages, most importantly eliminating the presence of electrical currents near the magnetically sensitive alkali vapor cell. The optical fiber based design allows for great flexibility, easy assembly, and possibly even smaller magnetic sensors.

The sensitivity is shown to be 2.6 $pT/Hz^{1/2}$ at 30 Hz, surpassing previously published results in a chip-scale magnetometer. Estimates show that by improvements in the thermal packaging the power consumption can be decreased to below 20 mW.

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