Invited Paper

# Prospects for atomic magnetometers employing hollow core optical fibre

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## ABSTRACT

Presently, among the most demanding applications for highly sensitive magnetometers are Magnetocardiography (MCG) and Magnetoencephalography (MEG), where sensitivities of around 1pT.Hz$^{-1/2}$ and 1fT.Hz$^{-1/2}$ are required. Cryogenic Superconducting Quantum Interference Devices (SQUIDs) are currently used as the magnetometers. However, there has been some recent work on replacing these devices with magnetometers based on atomic spectroscopy and operating at room temperature. There are demonstrations of MCG and MEG signals measured using atomic spectroscopy These atomic magnetometers are based on chip-scale microfabricated components. In this paper we discuss the prospects of using photonic crystal optical fibres or hollow core fibres (HCFs) loaded with Rb vapour in atomic magnetometer systems. We also consider new components for magnetometers based on mode-locked semiconductor lasers for measuring magnetic field via coherent population trapping (CPT) in Rb loaded HCFs.

**Keywords:** Magnetometer, optical sensor, atomic spectroscopy, semiconductor mode-locked laser

## 1. INTRODUCTION

This paper describes our current progress towards an atomic magnetometer based on coherent population trapping (CPT) in an atomic vapour (e.g Rb vapour) contained in a hollow core optical fibre [1]. The magnetometer is designed for biomagnetism applications such as Magnetocardiography (MCG) and Magnetoencephalography (MEG) [2].

In this paper we describe the

### 1.1 The fibre magnetometer and Biomagnetism

The layout of the proposed fibre magnetometer is illustrated in figure1. The coherent population trapping effect is used to sense the magnetic field because the hyperfine splitting of the ground state is sensitive to magnetic field. Typically a coherent population trapping measurement uses modulated light that has sidebands separated by the hyperfine splitting energy. For example if $^{87}$Rb is employed as the atomic vapour, then for the D1 line the light has a wavelength close to 795nm (377 THz) and the sideband separation is ~6.8GHz. The sensitivity of the $^{87}$Rb splitting to magnetic field is approximately 7GHz/T.

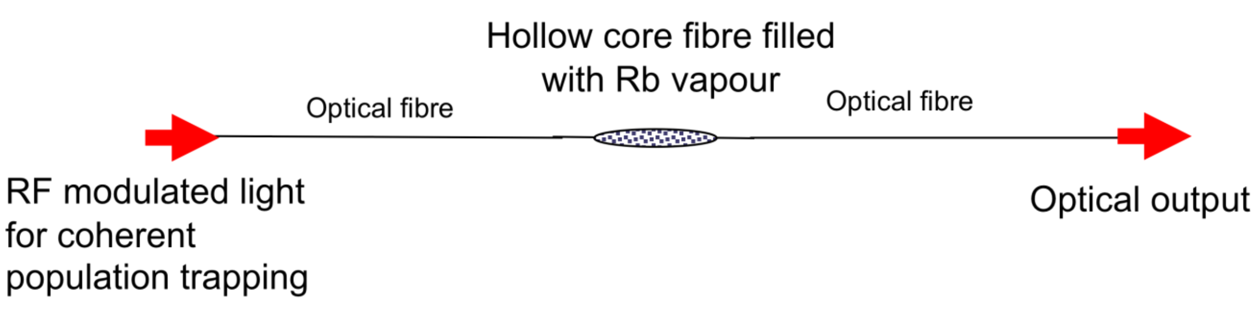


Figure 1. Schematic of the proposed fibre magnetometer : the input is radio frequency modulated light that is guided by conventional fibre to a hollow core fibre containing atomic vapour – the magnetic field at the hollow core fibre is sensed via the coherent population trapping effect.

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The proposed application is biomagnetism and an outline schematic of the proposed set-up for MEG is shown in illustrated figure 2. A similar system could be used for MCG. For MEG the target magnetic field sensitivity is $1fT.Hz^{-1/2}$ and $1pT.Hz^{-1/2}$ for MCG.

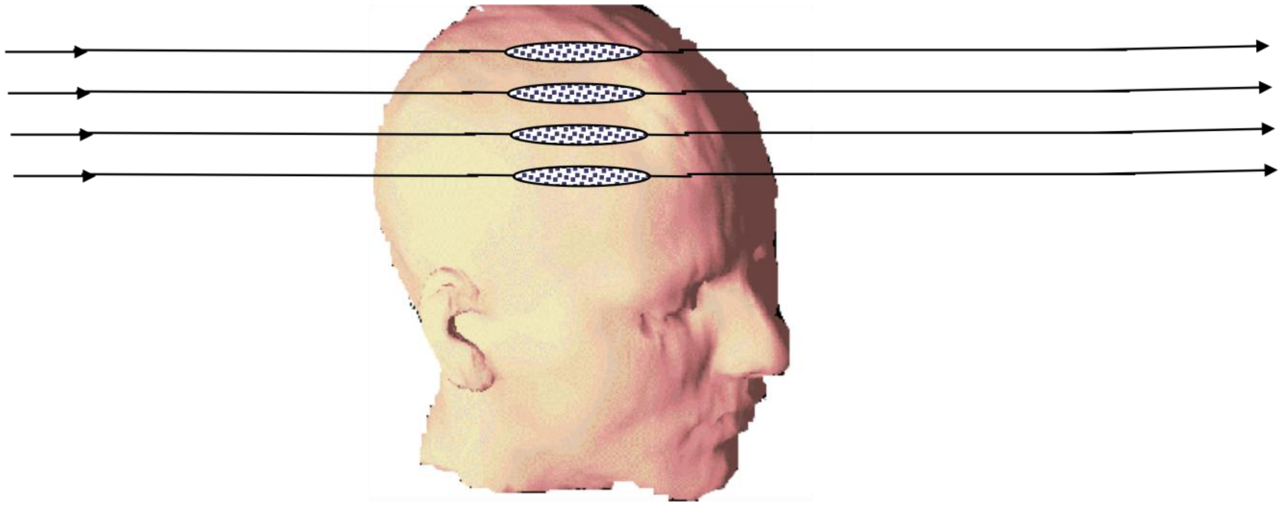

Figure 2. Schematic of the proposed arrangement of fibre magnetometers for MEG an array of several hundred magnetometers would be required for an neural activity imaging system.

### 1.2 The Hollow core fibre filled with Rb.

The hollow core fibre (HCF) can be filled with Rb vapour ; the technique for filling the HCF is described in detail in [1] and we give an outline review here. Figure 3 (taken from [1]) shows a scanning electron micrograph (SEM) the cross – section HCF.

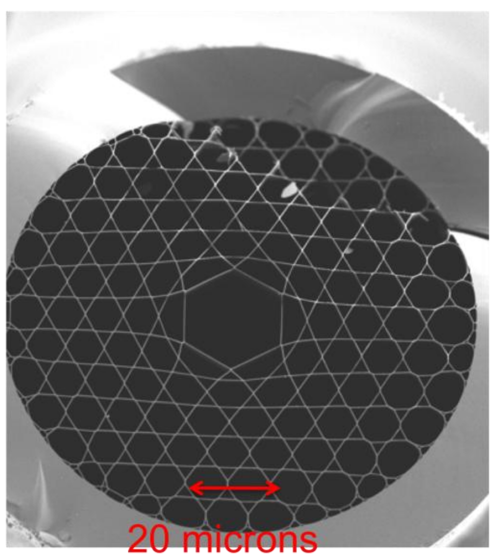


Figure 3. SEM of the end of the hollow core that is filled with Rb vapour [1]

The HCF is placed in a vacuum system and the Rb vapour takes a few days to load into the fibre – a spectroscopy system is used to monitor the absorption at the atomic absorption lines as the vapour is loaded into the HCF.

The coherent population trapping effect has been measured in the HCF [1] and Figure 4 shows the result.

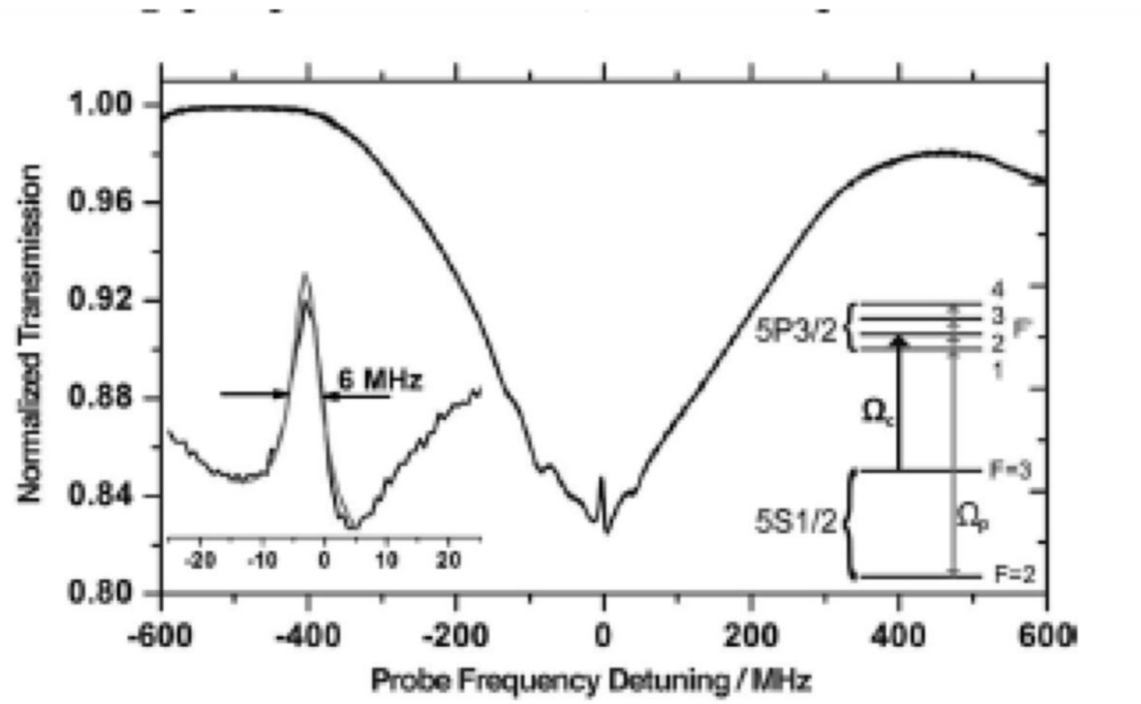


Figure 5. Measurement of the coherent population trapping (CPT) effect in a HCF loaded with Rb.- the insert shows the linewidth of the CPT effect [1]. Insert on left enlarges the scale of the CPT effect -20 to +20 MHz; the insert on the right shows the labeling of the atomic energy levels

# 2. MONOLITHICALLY MODELOCKED LASER DIODES FOR COHERENT POPULATION TRAPPING

## 2.1 Monolithically modelocked laser diode (MMLDs)

MMLDs are similar to conventional semiconductor lasers diodes except they incorporate a saturable absorber that passively modelocks the laser [3]. The MMLD has electrically separate sections - typically a forward biased section that provides optical gain and a reversed biased section that acts as a saturable absorber that is as the intensity is increased the absorption of light decreases – this passively modelocks the lasers. Figure 6. Illustrates the MMLD.

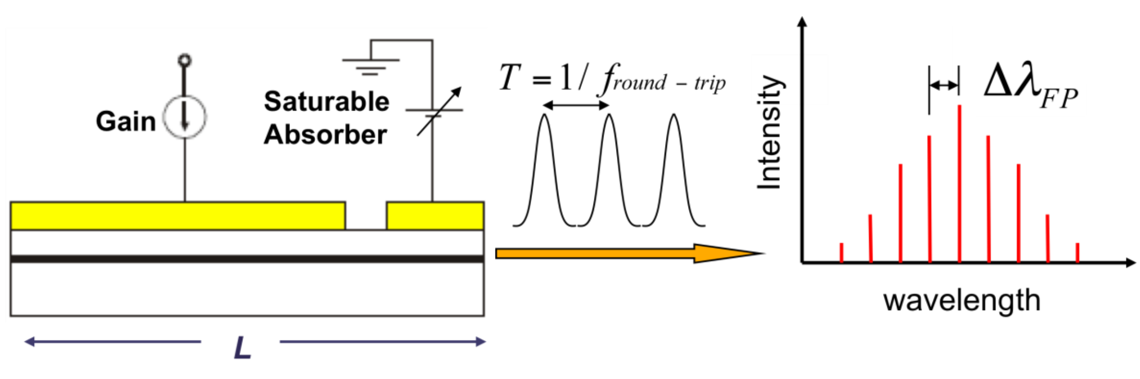


Figure 6. Schematic of a MMLD; the laser electrically separate sections - gain and saturable absorber sections. The saturable absorber section passively modelocks the laser and the laser produces pulses at repletion rate determined by the resonator round trip time.

For CPT the objective is to set the repetition frequency at the hyperfine splitting frequency, for example ~6.8GHz for Rb and the laser output wavelength should be at 795nm for the D1 line of Rb. The repetition rate is set by the following equation :-

$$f_{round-trip} = \frac{C}{2Ln_g}$$

where $C$ is the speed of light in a vacuum, $n_g$ is the group refractive index and $L$ is the length of the laser, $n_g$ is set by the design of the layer structure of the wafer [3], it is also temperature sensitive -L can be adjusted during fabrication. For $f_{round-trip}$~6.8 GHz then L ~ 5.7mm . So the repetition rate is set by altering the length of the laser to approximately 5.7mm and fined tuned by altering the current in the gain section which fine tunes $f_{round-trip}$ mostly via the temperature dependence of $n_g$

This technique of repetition rate tuning of a modelocked laser to measure the CPT has been observed previously[4] but not with a MMLD operating at the fundamental frequency of the CPT effect but using a Ti:Sapphire laser with a much lower repetition rate and relying of the $57^{th}$ harmonic of the repetition rate.

### 2.2 Results from Monolithically modelocked laser diode (MMLDs)

The MMLDs were characterised by measuring the output power as a function of input current in the gain section and reverse bias voltage; the pulsewidth and repetition rate were also measured as a function of input current in the gain section and reverse bias voltage. The repetition rate frequency and linewidth were measured using an RF spectrum analyzer. The output wavelength for best modelocking condition was measured using an optical spectrum analyzer.

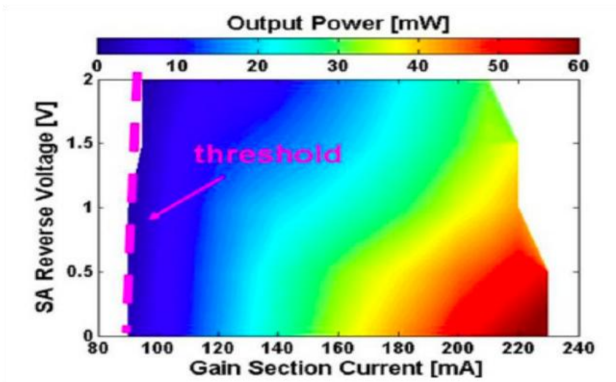


Figure 7. A map of the output power from the MMLD as a function of saturable absorber reverse bias and gain section current

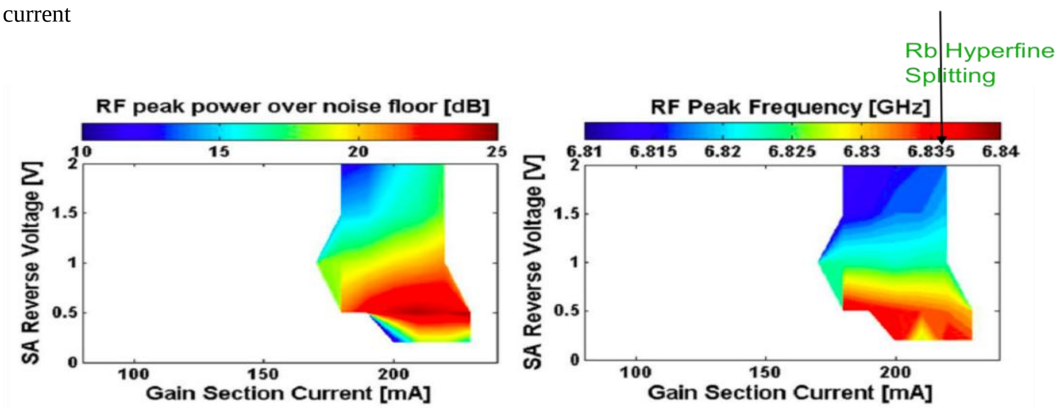


Figure 8. A map of the repetition rate strength of signal and frequency as a function of saturable absorber reverse bias; the Rb hyperfine splitting frequency is marked.

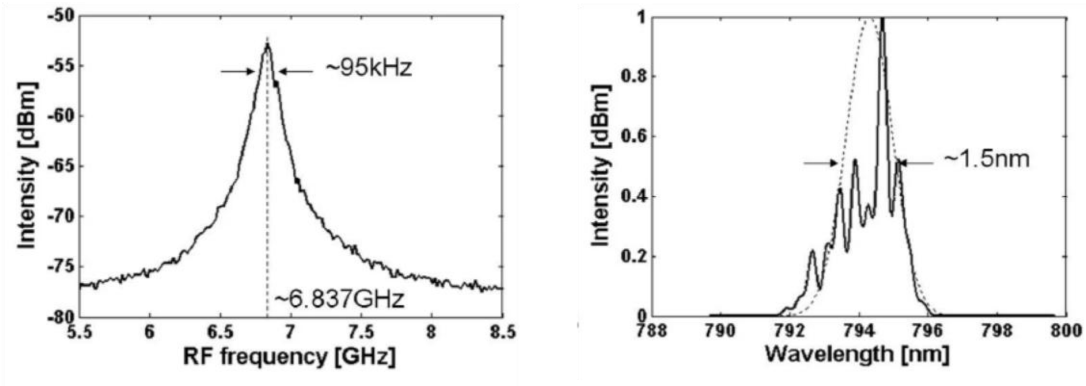


Figure 9. The rf and optical spectra of the output from the MMLD.

These results (figures 7-9) show that the MMLD produces around 48mW average power in best modelocking conditions and that it emits at 795nm. In figure 9 we show that the linewidth of the repetition rate is around 95kHz for this passively modelocked MMLD.

## 3. CONCLUSIONS

We have produced an MMLD with many of the correct characteristics for observing CPT in a HCF loaded with $^{87}$Rb vapour and thereby making sensitive magnetic field measurements. The MMLD emits enough power at the correct wavelength and tuning the gain current allows the repetition rate to tune through the hyperfine splitting of $^{87}$Rb. But the linewidth of the repetiton rate is 95kHz and this probably too large to observe CPT and certainly needs to be smaller if we are to achieve sensitivities of 1pT.Hz$^{-1/2}$ suitable for MCG.

## REFERENCES


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