DETECTION OF GROUNDWATER THROUGH ULTRA-SENSITIVE MAGNETIC MEASUREMENTS WITH ULTRA-SHORT PULSE LASERS

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DISCLAIMER

ABSTRACT

The goal of this project is to develop instrumentation to detect sources of groundwater or monitor the growth/decay of large aquifer layers through changes in magnetic susceptibility. Two approaches are being pursued: either by developing instrumentation capable of detecting minute changes of the vertical component of the earth magnetic field, averaged over large distances, or instrumentation capable of directly measuring changes in magnetic susceptibility. The common thread in these instrumentations is the use of ultrashort pulse ring lasers as differential phase spectrometers. The basic principle is to translate a differential phase shift into a frequency difference between the two output beams of a ring laser. Magnetic field changes are translated into phase shifts when the intracavity beams traverse a resonant atomic vapor inside the cavity. New stabilization techniques had to be developed to stabilize the pulsed laser to a narrow atomic transition. Basic stabilization research was performed with a Ti:sapphire laser. Optical parametric oscillators and solid state diode pumped lasers were developed in order to lead to a practical instrument that could be used in the field. Progress on fiber laser research leading to the development of magnetic susceptibility detector is also reported.

Contents

1 Introduction

Any material is characterized by electric or magnetic properties — quantified as the electric and magnetic susceptibility of the material. A measurement of these physical quantities over a given volume reflects the composition of that volume. Magnetic properties are more attractive than electrical properties for remote sensing because magnetic fields cannot be shielded as electric fields can. Wet soil has a slightly different magnetic permeability than dry soil. A direct measurement of the average magnetic permeability over a region extending to several hundred meters deep would provide a direct method of mapping and monitoring large aquifer layers. The difficulty is that the difference in magnetic permeability between dry and wet soil is minute. The change of permeability $\Delta\mu$ relative to that of the background material (soil) μ_{av} is $\Delta\mu/\mu_{\mathrm{av}} \approx 0.4 \cdot 10^{-3}$ [1]. An instrument that has the spatial range, the dynamic range and the sensitivity to measure such a small change in susceptibility over such a large average volume does not exist. Attempts to develop the first such instrument are reported in Section 6 on Fiber Laser Implementation.

A small change in magnetic susceptibility creates a small distortion of the earth's magnetic field lines. By mapping and monitoring the vertical component of the earth's magnetic field over a large region, it should be possible to recognize patterns associated with large aquifer layers. The ideal instrument should have a very large dynamic range, with a nonlocal response (i.e. averaged over a distance on the order of a meter), and an extreme sensitivity to minute changes in field. Aerial mapping of the earth magnetic field, using sensitive magnetometers, has been used successfully to locate minerals, in particular magnetic iron deposits and nickel deposits [2]. Instrumentation that is more sensitive than the one that was adequate for mineral search, and can average over larger areas, has to be developed. The most sensitive magnetometer is the superconducting weak link detector or SQUID [3], which provides only microscopic information, and has a limited dynamic range. This report detail progress made toward the development of an instrument, based on ultrashort pulse lasers that can achieve the requirement and objective of quifer detection. The advantages of the instrument we are developing include higher sensitivity without the frequency limitation of the SQUID, and a larger dynamic range, all properties important for aerial detection of aquifer layers.

The successive steps envisioned for this project were:

1. Conceptual demonstration of the method(s)
2. Development of laboratory prototypes to achieve the extreme sensitivities and dynamic range required
3. Development of laser prototypes that can be used in mobile units
4. Packaging of the selected systems in instruments that can be flown in a plane
5. Search for a "signature" of groundwater by scanning the instruments over known aquifer layers.

The progress reported here covers only areas (1) through (3). The basic principle of the method presented here involves measuring the change in index of refraction induced by a magnetic field, or, in the last implementation, a change in index that is proportional to a change in magnetic susceptibility. The sensitivity of our approach stems from the use of a ring laser itself as a differential interferometer, in which the change in index is translated into a frequency, as detailed in Section 2. It is necessary to have the laser operating as a continuous source of ultrashort pulses (cw mode-locked) in order for the system to respond to very small changes in index. The various implementations reported in the successive sections refer to different methods of obtaining counter-circulating pulse trains in a ring that do not interact with each other, but have a fixed crossing point. Optimal magnetic field sensitivity requires the use of a material for which the index change due to a magnetic field is maximal. Atomic vapors, such as used in potassium magnetometers [4], have a large resonant Faraday rotation, hence a large magnetic field induced change in index for circularly polarized light. In order to reach a better sensitivity than the superconducting magnetometer, initial tests have shown that it is necessary to stabilize the laser to the atomic line selected as magnetic field sensor. Stabilizing a ring laser that produces a continuous train of ultrashort pulses is a very challenging task and a fundamental research project in itself. Progress in this area is reported in Section 3. The stabilized laser must be locked to an atomic vapor. For the laboratory experiment, we have chosen a two-photon resonance of Rubidium.

The aforementioned basic research is performed on large, environmentally sensitive, bulky, inefficient, and expensive lasers. The use of liquid dye jet as the saturable absorbers makes them totally unsuitable for field applications. Therefore, we have been pursuing different laser concepts that can be packaged in a compact instrument. The first of these concepts that sidesteps the need for a liquid absorber is the optical parametric oscillator (OPO), detailed in Section 4. Here again, the research prototype has been an OPO pumped by a Ti:sapphire laser, itself pumped by an argon ion laser, a $110,000 combination requiring 480V/60 A electrical power, and 5 gallon/minute cooling water. The Ti:sapphire pump laser could be replaced by a more economical diode pumped solid state laser. Developing such a laser will be pursued once all the OPO ring laser properties have been completely characterized.

In terms of compactness and robustness, the most appealing approach is the solid state mode-locked ring laser directly pumped by laser diodes. Progress on this last concept is reported in Section 5.

The only laser that can make direct susceptibility measurements is the fiber optic laser. Obtaining bidirectional mode-locked operation is a particularly challenging endeavor, and is reported in Section 6

2 Concept and basic principles

2.1 Mode-locked ring lasers as sensors

The properties of a ring laser are somewhat similar to those of a linear laser. In order for the electromagnetic wave to repeat itself in the resonator, the perimeter P should be an integer number of wavelengths λ, i.e., $P = N\lambda$, where N is a very large integer. Two beams, corresponding to either direction of circulation in the ring, can be extracted through an output mirror of the laser, and made to interfere on a detector. The light that circulates clockwise and counterclockwise in the ring cavity goes through the same optical path and the same optical elements. Therefore, the perimeter in the clockwise direction P_+ should be equal to the perimeter in the counterclockwise directionP_-, and the detector should see a continuous signal. However, any perturbation that affects one direction of circulation differently from the other may result in an unbalance of the perimeters, hence a different wavelength $\lambda_+ = P_+/N$, and $\lambda_- = P_-/N$ for the two different directions of circulation. The detector will then record an alternating signal or "beat note" of frequency $\Delta\nu$ equal to the difference between the two optical frequencies $\nu_+ = c/\lambda_+$ and $\nu_- = c/\lambda_-$, where c is the speed of light. It can easily be shown that the frequency of this beat note is given by:

$$\Delta\nu = \nu\frac{\Delta P}{P}, \quad (1)$$

where P is the average cavity perimeter. However, any light injected in a laser cavity at a frequency close to that of the laser will modify the laser frequency (in general, force the laser to operate at the light of the injected radiation). In a ring laser operating in a continuous mode, there is always light scattered from all the optical elements (gain medium, mirror) from one sense of circulation into the other. This scattering generally locks the frequencies ν_+ and ν_- to the same average value, and there is no beat note $\Delta\nu$ to be observed. We have shown [5] that the situation can be different in mode-locked ring lasers, where two very short pulses(pulse duration τ of the order of 100 fs or 10^{-13} s, pulse length $c\tau$ of the order of 30 μm) circulate in the ring in opposite direction. The two circulating pulses can only scatter into each other where they meet. By controlling the meeting point of the pulses (for instance, forcing them to meet in air or vacuum), and/or controlling the properties of the medium at the crossing point (no scattering that would couple the wavelength of the two beams), it is possible to record extremely small (of the order of 1 Hz) frequency differences between the two output beams. An example of such a beat note is shown in Fig. 1. It is remarkable

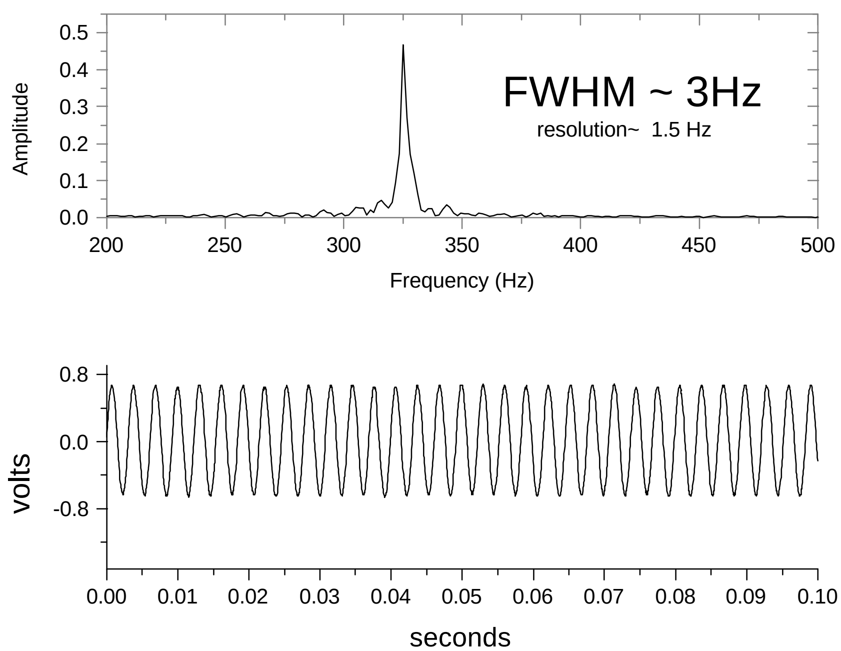

Figure 1: Below: typical beat signal recorded with a Ti:sapphire mode-locked ring laser. Above: Fourier transform of the time trace.

that, even though the bandwidth of each output of this laser is of the order of THz, the beat note bandwidth is only 3 Hz. According to Eq. (1 the 325 Hz signal indicates a difference in cavity length of only 0.015 Åfor the two directions. With this instrument, we can resolve a variation of beat note of 1 Hz, which translates into a variation of optical path of less than 10^{-14} m or 0.01 pm. The extreme sensitivity of the mode-locked ring laser to a minute differential between the two senses of circulation stems from Eq. (1): a minute relative optical path difference $\Delta P/P$ between the two directions is multiplied by the light frequency ν, which is a huge number (order of 10^{15} Hz). The mode-locked bidirectional ring laser can also be viewed as a differential interferometer. Any phase shift/round-trip $\Delta\varphi$ between the oppositely circulating beams, is converted into a beat frequency $\Delta\nu = \Delta\varphi/\tau_{rt}$, where τ_{rt} is the round-trip time for the pulses circulating in the cavity. A beat note of 1 Hz implies that a differential phase shift of 10^{-8} radian has been detected in a typical ring resonator. As will be shown in the next subsection 2.2, the differential phase shift $\Delta\varphi$

can be created by a magnetic field. The bandwidth of the beat note as in Fig. 1, which sets the resolution limit of the device as, for instance, a magnetometer, is due to vibrations of the mirrors. Indeed, because of random vibrations of all the components of the cavity, and in particular the mirrors, there are random fluctuations of the optical path seen by the pulses in either direction, during the time of a cavity round-trip. In a typical cavity, the round-trip time is of the order of 10 ns. Assuming that the mechanical components (mirror mounts, laser support) have a resonance frequency around 100 Hz (or a period of mechanical oscillation of $T_{\rm mech} \approx 10$ ms), the 3 Hz bandwidth corresponds to $(\Delta P)_{\rm mech} \approx 2 \cdot 10^{-14}$ m, or an amplitude of mechanical oscillation at resonance of $d_{\rm mech} \approx 20$ nm. Active stabilization of the cavity length can substantially reduce the amplitude of these random fluctuations in cavity perimeter $(\Delta P)_{\rm mech}$, thereby pushing further the detection limit of the device. With this goal in mind, we have started a research program on stabilization of a mode-locked Ti:sapphire laser. Our progress in this area is reported in Section 3.

The basic topology of the laser and detection principle are illustrated in Fig. 2. Some passive or active mechanism forces laser operation to be a train of ultrashort ($\ll 1$ ps or 10^{-12} s) optical pulses, circulating in opposite direction in the laser resonator. The resonator can consist of an arrangement of mirrors (in which case the "ring" is essentially a polygon), or a fiber waveguide. Such a laser has at least two outputs, one for each direction of circulation. In Fig. 2, the two outputs are recombined on a single detector. An adjustable optical delay is used to ensure that pulses from either output channel meet at the detector. The detector records a train of identical ultrashort pulses, separated by the round-trip time of the laser cavity. If there is a difference in optical frequency between the outputs corresponding to the two senses of circulation in the laser cavity, the amplitude of the pulse train will be modulated at the difference frequency between the two directions, as shown in the insert.

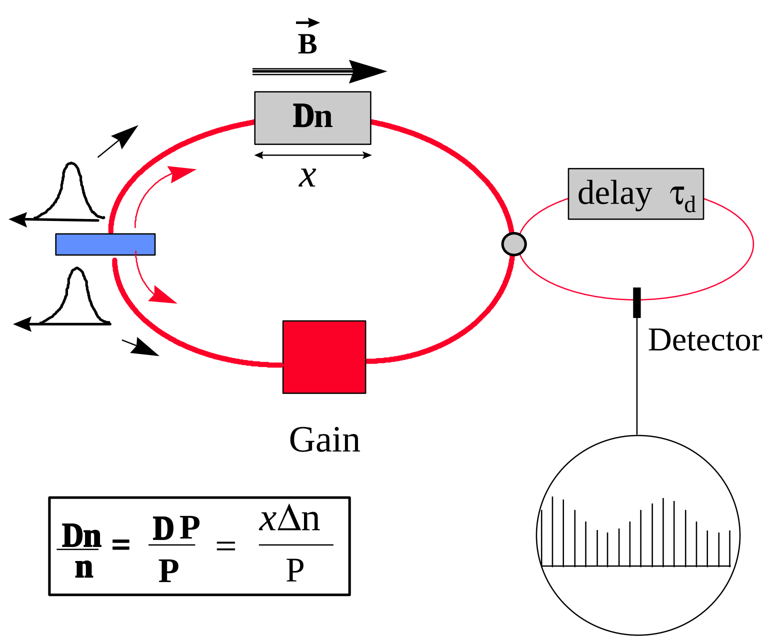

Figure 2: Topological sketch of the short pulse ring laser sensor, showing the two outputs (to the right) recombined via an optical delay line on a detector. When a magnetic field $\vec{B}$ is applied to a transparent sample of length x, the Faraday effect will manifest itself as a small differential change in index Δn for the beams propagating in opposite direction through that sample. As a result, there will be a small difference ΔP for the optical perimeter seen by the pulses circulating in opposite direction.

The short pulse requirement is necessitated by the condition that the two pulses should never meet at an optical component (solid or surface), which would cause the two wavelengths to be coupled by scattering [1]. The absence of coupling between the two directions requires that the crossing point be several pulse length away from any optical component, a condition that is easily met for a 100 fs pulse, which has a length of the order of 30 μm [5].

2.2 Magnetic field detection

If the index of refraction of an element of length ℓ in the cavity (perimeter P) differ for the two sense of circulation by Δn, the beam circulating in opposite direction will see a difference in perimeter $\Delta P = \ell \Delta n$. The change in index of refraction Δn between the two directions can, for instance, be caused by a magnetic field. It is particularly interesting for this application that the measurement can be integrated over a long distance ℓ. The longer the optical path over which the index is changed, the larger the signal. For our application, either a change in magnetic field or susceptibility will be converted in a differential path (or phase) difference between the counter-rotating beams of the laser.

There are various geometries possible for the laser, in which a magnetic field is converted into a phase shift, of opposite sign for the two pulses that circulate in the ring cavity. In all cases, a circularly polarized beam is made to propagate along the direction of the magnetic field to be detected. The right-handed polarized radiation will have a slightly different phase velocity, or wave vector, than the left-handed one. For consideration of magnetic field induced optical phase shifts, it is more convenient to use coordinates oriented with one axis along the magnetic field. One geometry of magnetic sensor uses the sensor material in the ring of the laser, as sketched in Fig. 3.

In the clockwise direction, the linearly polarized pulse becomes right circularly polarized after transmission through a quarter wave plate, suffers a phase shift through the magnetic field sensitive sample S, acquires a polarization orthogonal to the original one after transmission through the second quarter wave plate. A half wave plate restores the polarization of the cavity. For the counterclockwise pulse, the half wave plate rotates its linear polarization by 90°. The quarter wave plate produces a left circularly polarized pulse, that suffers the opposite phase shift through transmission through the sample S. The differential phase shift/round-trip produces the beat note on the detector D.

Another possible configuration for magnetic field monitoring is the ring with a straight appendix as sketched in Fig. 4. In this configuration, the counter-clockwise circulating pulse is reflected by the polarizer P, converted into circular polarization by a quarter wave plate, suffers a phase shift after a **round-trip** through the magnetic field sensitive material S, is transformed into linear - orthogonal polarization with re-transmission through the quarter wave plate, and continues its circulation in the main ring after its polarization is returned to its original orientation by a half wave plate. The clockwise beam retraces the same path in reverse, except that the circular polarization in the linear tail has the opposite sign. A magnetic field parallel to the tail induces a path length difference for the counter-rotating pulses, which results in a beat frequency on the detector. We have demonstrated the operation of such a laser configuration (ring with tail) [6].

There are various choices that can be made for the material S. One can use either the non-resonant Faraday effect in solid-state materials such as glasses, or a resonant Faraday effect of resonant vapors. Considerations of losses and sensitivity have shifted our choice towards the resonant vapor. A brief discussion of the relative properties of both approaches is given below.

[1] This results in the “dead band” in a laser gyro.

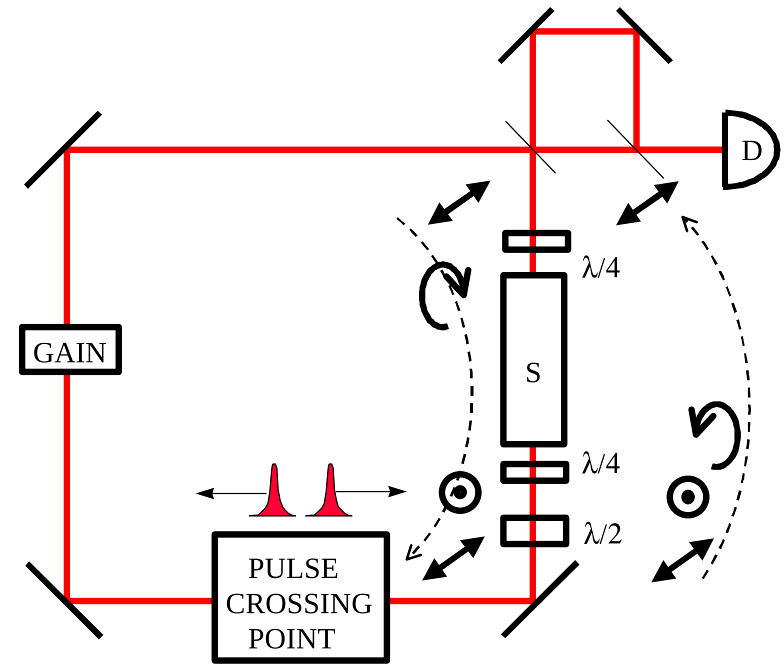

Figure 3: Monitoring a magnetic field with a pulsed ring laser. S designates a material producing a differential phase shift for left- and right- circularly polarized beams, proportional to the component of a magnetic field along the propagation direction of the beam.

2.2.1 Non-resonant materials

It has been proposed originally to use optical glasses with a high Verdet constant. The difference in optical phase seen by circularly polarized light propagating through a transparent medium of length ℓ, of Verdet constant V, along a magnetic field H is $\Delta\varphi = V\ell H$, which, as part of a laser cavity of round-trip time τ_{RT} will induce a beat note of frequency:

$$\Delta\nu = 4\frac{\Delta\varphi}{\tau_{\mathrm{RT}}} = 4\frac{V\ell H}{\tau_{\mathrm{RT}}}. \tag{2}$$

The factor 4 reflects the fact that the light *of each circular polarization* makes a round-trip through the tail, experiencing twice the single passage phase shift, and that the beat note is the difference of opposite phase shifts for each circular polarization, divided by the cavity round-trip time.

Most transparent materials have a Verdet constant larger than that of fused silica, which is $V_s = 0.510^{-5}$ radian/(Gauss cm) = 5 radian/(Tesla m). Substituting in Eq. 2, one finds that the resolution of 1 Hz beat note as in Fig. 1 corresponds, for a 10 m fiber sensor element, to a magnetic field variation of:

$$\Delta H = \frac{\Delta\nu\tau_{\mathrm{RT}}}{4V\ell} = 3.5 \cdot 10^{-10}\ T, \tag{3}$$

where we have assumed a cavity round-trip time of 70 ns. Such a configuration with a long fiber has the advantage of recording a magnetic field average over a longer distance. There are, however, considerable losses associated with the fiber tail, which cannot be overcome by the gain of a Ti:sapphire laser. A high gain semiconductor or fiber laser should be used for this purpose. Progress in this area is reported in Section 6. Another possibility is to use shorter cavities, with bulk glasses which can have a 100 times larger Verdet constant. A device such as the one sketched

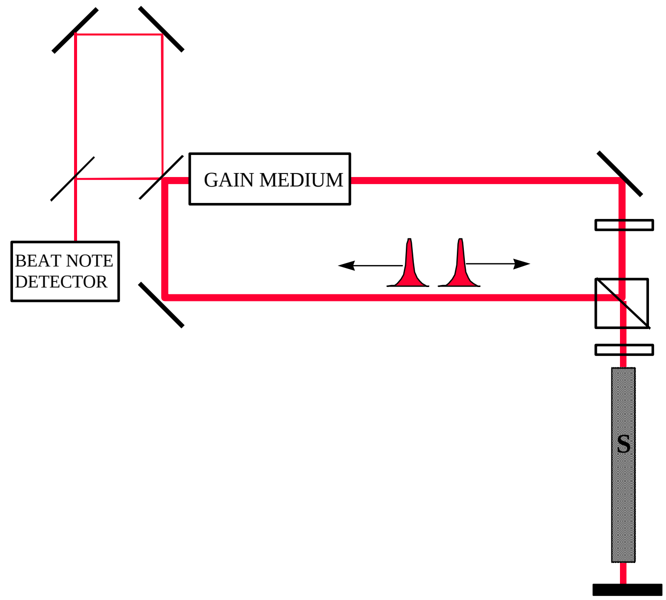

Figure 4: Monitoring a magnetic field with a pulsed ring laser with a tail containing material S inducing a different phase shift for right and left circularly polarized beams, proportional to the component of the field parallel to the tail. The differential phase shift/round-trip results in a beat note on the detector, proportional to the magnetic field.

in Fig. 4 will be sensitive to changes in magnetic field as small as $0.1 \cdot 10^{-10}$ Tesla or 0.01 nT. This is one order of magnitude less sensitive than the superconducting magnetometer or SQUID. In addition to the reduced sensitivity, the non-resonant material has the disadvantage of a relatively large absorption coefficient at the wavelength of the Ti:sapphire, which is the only laser at our disposal at the start of this project.

2.2.2 Resonant material

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The sensitivity of our device can be enhanced several orders of magnitude by exploiting the huge enhancement of phase shifts occurring near an atomic resonance. We have demonstrated theoretically and experimentally this effect with a ring-dye laser and samarium vapor for the atomic resonance [6]. With 10 cm of optical path through the samarium, in the configuration of Fig. 4, computer simulation [6] shows that the response of the device to be 100 MHz/(0.01 Gauss) or 1014 Hz/T. Thus, one Hz resolution in beat note corresponds, in this configuration, to being sensitive to a change in magnetic field of 10^{-14} T. Several orders of magnitude enhancement of sensitivity are expected through a better choice of material (narrower resonance, higher vapor pressure) and stabilization of the laser. Because of the availability of the laser, our present efforts are aimed at locking the laser wavelength to either a single photon (5S-5P), or the two-photon Doppler free 5S-5D resonance of rubidium at 778.1 nm. As mentioned previously, by stabilizing the wavelength of the laser, one improves the sensitivity limit of the device by reducing the linewidth of the beat note. In the case of a laser with an intracavity atomic cell, stabilization is essential when the linewidth of the transition to which the laser is stabilized is narrower than the mode spacing of the laser.[2]

[2] The cavity length of the laser has to be locked to an integer number of wavelength, at the wavelength corresponding

2.3 Detection of small magnetic susceptibilities

The previous sections relate to indirect measurements of susceptibility through the changes in the earth's magnetic field. The research with fiber-ring lasers is aimed at constructing a device that interrogates materials, by generating its own (alternating) magnetic field.

The possibility to use the short-pulse ring laser as ultra-sensitive detector of magnetic susceptibilities, stems also from the phase sensitivity of the device. The next few paragraphs will show that the short-pulse ring laser can be used to provide a signal of which the frequency is proportional to the phase drift between an oscillator and the laser itself (used as a reference oscillator). Conventional instruments used to measure changes in susceptibility (metal detectors) measure the change in resonant frequency of an oscillator, as the magnetic susceptibility in a coil of that oscillator is modified. We can achieve up to several orders of magnitude higher sensitivity by providing a frequency change proportional to the phase shift of that oscillator.

2.3.1 Electro-optic dither

Some realizations of the short-pulse ring laser will still experience a small coupling between counter-rotating beams (see Section 5), leading to a dead band. This dead band has to be eliminated in order to be able to create a device with high magnetic field sensitivity. A similar situation is encountered in commercial laser gyros, which are He-Ne continuous-wave ring lasers. In these commercial lasers, a mechanical motion is given to the whole assembly, to bias the response away from the dead band. One of the advantages of the short-pulse laser gyro over the conventional continuous wave gyros, is that it is particularly easy to impose a dither or bias rotation, without physically rotating the device. The principle of beat note control through an optical modulator is shown in Fig. 5. One of the output pulse trains of the laser is sent through a delay line before

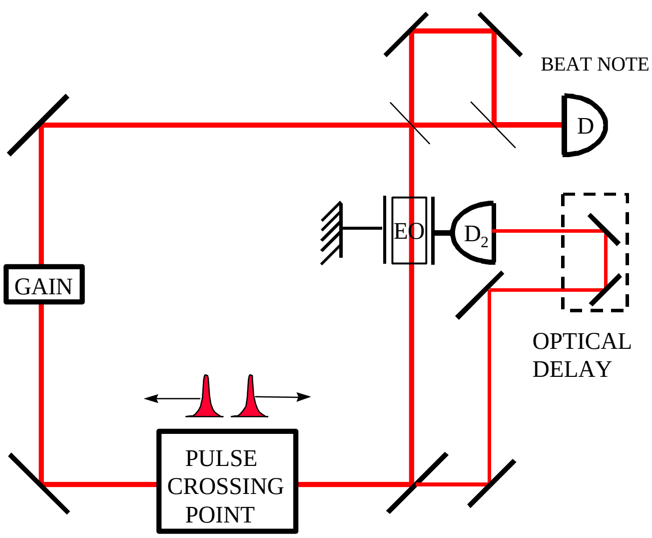

Figure 5: Creating and controlling an artificial beat note.

being recorded by a detector D_2. The output of that detector is applied directly to the electrodes of a nonlinear crystal (for instance $LiNbO_3$). If the length of the optical delay line is such that a maximum voltage is applied at the exact time that the counter-clockwise pulse enters the crystal,

to the transition to which the laser is stabilized.

the field induced change in refractive index will result in a longer cavity for the counter-clockwise pulse than the clockwise pulse, hence a beat note will result. Depending on the particular parameter being detected (rotation, magnetic field), this beat note can be seen as a bias signal. One technique to eliminate the bias, while still using its property to eliminate the dead band, is to multiply the signal applied to the $LiNbO_3$ by a symmetric square wave, at a frequency much higher than the signal frequency to be measured. This technique is used to eliminate the bias and dead band in the semiconductor laser pumped solid-state ring laser (see Section 5).

2.3.2 Beat note as a measurement of the phase of an oscillator

It is important that the signal applied to the modulator has a constant amplitude. Any amplitude noise on that signal will result in frequency fluctuations of the beat note. One technique to improve the amplitude stability (hence reduce the beat noise bandwidth increase due to detector noise) is to use an electronic oscillator providing a fixed frequency equal to the repetition rate of the ring laser, as sketched in Fig. 6. The beat note will be a function of the relative phase of the oscillator

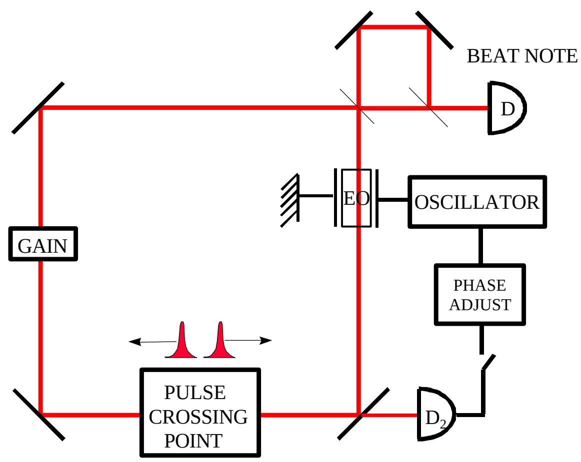

Figure 6: Controlling a bias frequency with an oscillator.

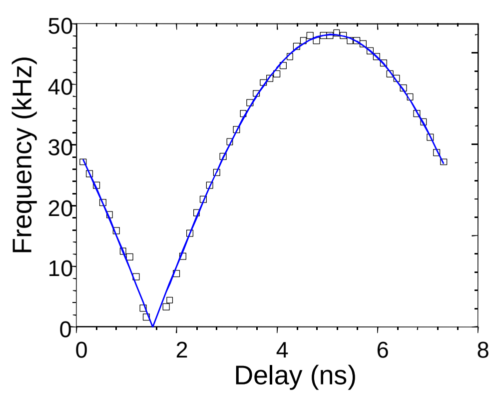

Figure 7: Measurement of the beat note as function of the phase of the electrical signal applied to the modulator (cf. Fig. 6).

and the intracavity pulse. If either pulse enters the lithium niobate modulator at the node of the oscillation, there will be no resulting beat note. As the relative phase between the oscillator and the laser is changed, the beat note frequency will vary from zero to a maximum, as shown in the measurement of Fig. 7. The measurement of magnetic susceptibility is based on the use of the beat note of the ring laser to monitor the drift in phase of an electronic oscillator, operating at the repetition rate of the laser cavity.

2.3.3 Principle of the detection of magnetic susceptibility

The frequency of an oscillator as in Fig. 6 is typically determined by a resonant circuit, containing a coil of inductance L as part of a resonant LC circuit. A change in susceptibility of the medium surrounding the coil results in a change $\Delta\omega$ in resonant frequency ω :

$$\frac{\Delta\omega}{\omega} = \frac{\Delta L}{2L} = \frac{\Delta\mu}{2\mu}. \tag{4}$$

By converting the phase drift between the oscillator at ω and a reference oscillator (the laser cavity) into a beat frequency (between counter-propagating mode frequencies of the laser), it is possible to achieve a sensitivity to resonant frequency changes as small as $\Delta\omega/\omega = 10^{-10}$. In order to have an instrument that can be useful for remote sensing, the wavelength corresponding to the oscillator frequency should be large compared to the range to be probed. The frequency of the oscillator, for our application, should be not higher than 1 MHz. This implies a cavity perimeter of the order of 300 m, which can only be achieved with fiber lasers.

The principle of operation of this approach is sketched in Fig. 8. The large circle is a topological representation of the ring laser, in which two pulses circulate in opposite directions, at the cavity round-trip time τ_{RT}. Let us assume the cavity is at equilibrium, with a zero beat frequency. If

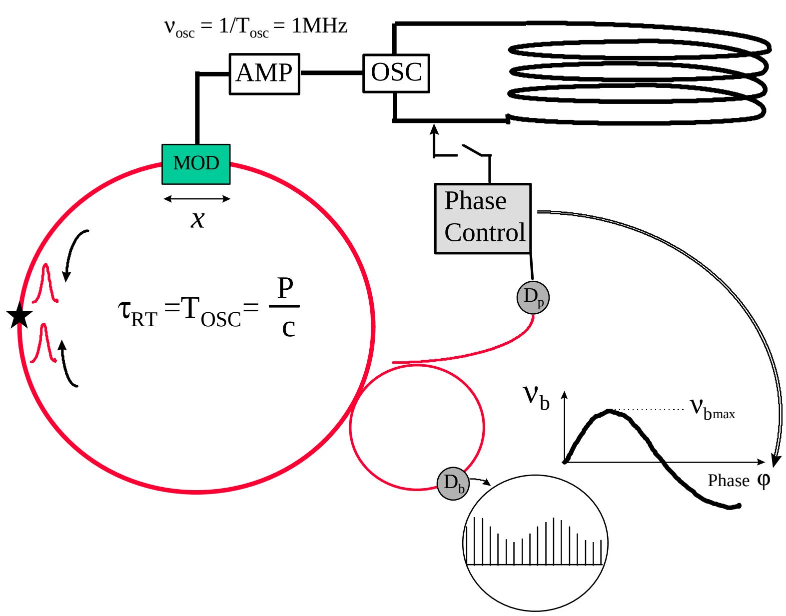

Figure 8: Beat note induced by electro-optic modulator driven by a synchronized oscillator, as a function of the relative phase.

an electro-optic modulator is inserted in the cavity, and driven at the cavity round-trip frequency

$1/\tau_{\rm RT}$, a beat note may or may not be observed, depending on the exact phase relationship $(\varphi_V)^3$ between the modulator voltage and the intracavity pulses [5, 7]. For $\varphi_V = 0$, both pulses enter the modulator at a node (zero voltage) of the electrical signal applied to it, and the beat frequency will be zero. The condition that will give the largest beat note is $\varphi_V = \pi/2$, with the clockwise pulse reaching the modulator at the peak of the sine wave, and the counter-clockwise reaching the modulator at the minimum of the sine wave. The maximum beat note ν_{bmax} depends on the particular electro-optic modulator being used, but can easily reach several MHz [5]. If Δn_max is the maximum index of refraction change induced in the modulator of length d under the applied voltage V_{max}, the maximum beat note is, according to Eq. 1 $\nu_{bmax} = \nu(d/P)\Delta n_{max}$.

The oscillator is periodically tuned to the cavity repetition frequency, and locked in phase with $\varphi = 0$. At periodic time intervals, the phase-lock loop input from the detector D is disconnected. A small change $\Delta\mu$ in magnetic susceptibility results in a shift δ in resonant frequency of the oscillator such that $\nu_{osc} = (c/P) + \delta$. As a result, the phase φ_V will drift to become, after a time t_{obs}: $\varphi_V = t_{obs} \times \delta$. The beat frequency will have changed from zero to: $\nu_b = \nu_{bmax} \times \delta t_{obs}$.

For a numerical estimate, let us assume a cavity round-trip frequency of $1/\tau_{\rm RT} = 1$ MHz, and a modulator providing a maximum beat note of $\nu_{bmax} = 100$ kHz. As the phase locking loop is released, the change in susceptibility induces a phase drift at a rate of 10^{-3} in an observation time of $t_{obs} = 10$ s. The beat note changes thus from zero to 100 Hz, which is easily detectable. The change of frequency of the oscillator that can be detected is $\delta = 10^{-4}$ Hz, or a relative change of $(10^{-4}$ Hz$)/(1$ MHz$) = 10^{-10}$. This is to be compared with a direct reading on a change of the frequency of the oscillator: a change in 100 Hz of oscillator frequency is a relative change of 10^{-4}.

3 Laser stabilization

There are two compelling needs to stabilize the mode-locked laser for the applications that we are contemplating:

- reduce the bandwidth of the beat note by eliminating, through stabilization, random fluctuations of the cavity perimeter. This reduction of bandwidth is synonymous to enhancing the sensitivity limit of the device
- have the laser frequency tuned at or near an atomic transition frequency, for use as magnetometer.

It is a standard technique to lock a continuous mode laser to an atomic transition. In the case of a mode-locked laser, which consists of a continuous train of ultrashort pulses, the stabilization is technically and even conceptually more challenging. The frequency spectrum of a mode-locked laser consists of a comb of frequency. Locking directly one tooth of that comb to an atomic resonance is technically difficult, in view of the very low power contained in that particular mode. We circumvent this technical problem by stabilizing first the mode locked laser to a high finesse, mechanically stable, Fabry-Perot reference cavity, of the same length as the laser cavity. Each pulse that has made one or several round-trips in the reference cavity can interfere with the successive pulses from the laser entering the reference cavity, since the repetition rates are matched. In the frequency domain, this corresponds to overlapping the modes of the laser and reference cavity, instead of using only the minuscule power contained in a single tooth of the frequency comb of the

[3] We have used a subscript V to distinguish this phase difference between electrical signal and time of arrival of light, from the phase shifts between light beams defined in Eq. 2.

laser. The reference cavity is made of a large (62.54 cm long) block of Ultra Low Expansion quartz (ULE), with zero thermal expansion at 22.5°C. Long-term stability is to be provided by pressure stabilizing the ULE cavity, to maintain a constant fluorescence from a selected atomic transition.

Beyond the technical difficulties, there are more fundamental challenges in the stabilization of the mode-locked laser, particularly important for its application as a sensor. The fundamental questions are:

1. Given that the frequency of one mode has been stabilized (or the central wavelength of each pulse has been defined), are the modes exactly equally spaced?
2. Does the average frequency of the laser correspond to one of the modes? If not, how can one set the laser repetition rate to be an integer number of optical cycles?
3. If the modes are equally spaced, how can the repetition rate of the laser be maintained constant (fluctuation of the repetition rate will cause the mode comb to "breathe" around the stabilized mode)?

The first and last points are quite crucial to the resolution of a ring laser as a sensor, since the beat note is made of the frequency difference between the corresponding tooth of the two counter-circulating combs of modes. A randomness in the mode spacing will immediately translate into a broadening of the beat note signal.

3.1 Equality of mode spacing

Since this is an important point for metrologic application, we have verified the equality of the mode spacing for a 9 femtosecond (fs) Ti:sapphire laser. A 0.2 nm bandwidth of the more than 130 nm broad output spectrum of the laser was selected with a monochromator, sent onto a fast photodiode, of which the signal was recorded with a frequency counter and a spectrum analyzer (Fig. 9). The sensitivity of the spectrum analyzer (spectral resolution 1 Hz) allowed us to measure far into the wings of the mode-locked spectrum, greater than 50 dB down from the center peak over a spectral region of 250 nm. The frequency counter on the other hand had a higher spectral resolution (0.1 Hz). The main source of error in the measurement arose from the thermal expansion of the cavity. This expansion appeared as a slow decrease in the pulse repetition rate, typically 5-10 Hz within the total measurement time of the experiment. However, due to the linearity of this drift, our measurement was only limited to an uncertainty of ± 1 Hz. The repetition rate of the different wavepackets does not vary as a function of frequency to within experimental error over a total span of 250 nm. Such a result is expected, since the different wavepackets formed with any group of modes should all travel at the same group-delay or they will not produce a pulse that "stays together" after several round-trips. A recent experiment [8] has confirmed that the inverse of the pulse repetition rate of a mode-locked laser is equal to the longitudinal mode spacing and that these modes are equally spaced to within an experimental uncertainty of 6.0 parts in 10^{16} and 3.0 parts in 10^{17}, respectively.

3.2 Stabilization of both average frequency and repetition rate

The mode-locked train can be visualized as a pure harmonic wave modulated by a periodic envelope. In general, the period of the envelope (pulse spacing) will not be an integer number of light periods (Fig. 10a), and the phase of the optical cycle relative to the envelope will change from pulse to pulse. In the frequency domain, this corresponds to a comb of frequencies of the mode-locked laser

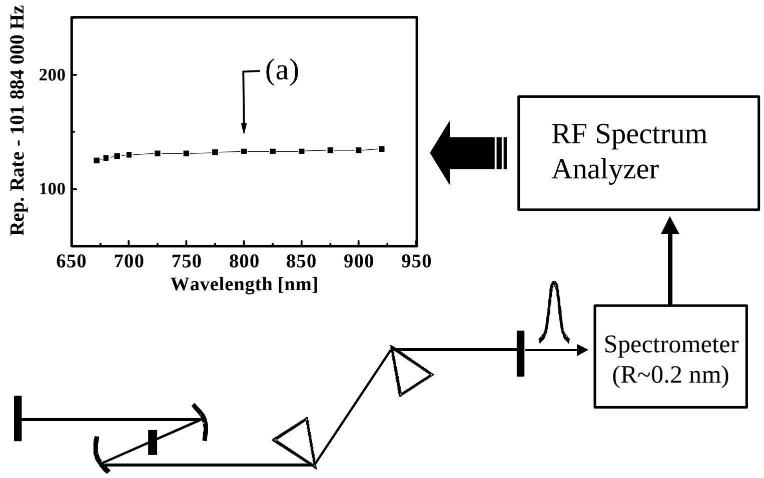

Figure 9: Schematic of experimental setup. The point indicated by position (a) corresponds to a measured repetition frequency of 101 884 133 Hz.

that are not exact higher harmonics of the pulse repetition rate, but rather offset in frequency due to the difference in the average phase and group velocity of the pulse. If a laser is stabilized to an atomic line, it is the average carrier frequency that is locked to that line. The position of the comb of modes with respect to that particular reference still needs to be defined.

In order to be able to use a narrow line atomic vapor inside the mode-locked laser cavity, it is necessary to devise a stabilization scheme that (i) stabilizes the repetition rate of the cavity to a stable clock, and (i) sets the repetition rate as a fixed fraction of the optical frequency. The optical frequency of a tooth m of the comb is:

$$f_m = m f_{rep} + (\Delta\phi/2\pi) f_{rep}, \tag{5}$$

where f_m is the optical frequency of the m^{th} mode, f_{rep} is the laser repetition frequency, and $\Delta\phi$ is the pulse to pulse carrier-envelope phase slip [9, 8, 10]. The two parameters to monitor, control and stabilize are thus f_{rep} and $\Delta\phi$. We present instead a purely optical method to stabilize both parameters, by coupling the laser to a stable, fixed Fabry Perot resonator.

The key element is a long (60 cm) Fabry-Perot resonator made of a solid block of Ultra Low Expansion quartz (ULE), with high reflectivity mirrors of the same material optically contacted on both ends. The ULE has zero thermal expansion coefficient at 22.5°C. It is acoustically and thermally isolated from the surroundings in a wooden box lined with polyurethane foam. We have shown in a previous paper how the transmission through this Fabry-Perot can be used to distinguish whether the repetition rate of the laser corresponds to an integer number of optical cycles in the reference cavity [10]. If the latter condition is met, the envelope of the transmission pattern through the reference cavity, as the cavity length of the laser is being scanned, has its axis of symmetry coincident with one mode of the cavity. We will use here the reference cavity to stabilize both a mode frequency, and the laser repetition rate.

Figure 11 shows a schematic of the experimental setup for locking the Kerr lens mode-locked Ti:sapphire laser to the reference cavity. The output of the laser, protected from feedback by a Faraday isolator, is sent through a phase modulator (PM), which adds two sidebands at $\pm$

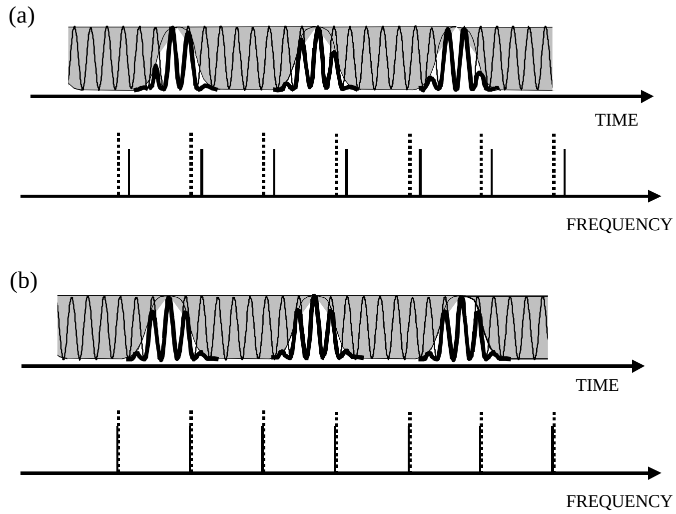

Figure 10: A mode-locked pulse train is sketched as a repetitive envelope gating a continuous wave. The corresponding mode structure of the pulse train is shown below in solid lines. The dashed lines indicate the position of the modes that are exact higher harmonics of the repetition frequency. Figure (a) illustrates the more general situation where the pulse repetition rate is not a multiple of the light period. This results in the frequency offset of the fs comb from the position of the exact higher harmonics as shown. Figure b shows the ideal case of "phase stabilized pulses" when the repetition frequency is an exact multiple of the light period. The important point of this figure is not the exact value of the relative phase of the envelope and oscillation, but that it stays the same from pulse to pulse.

10.7 Mhz to each of the tooth of the frequency comb. Double path through an acousto-optic modulator (AOM) provides control on the position of the whole frequency comb, without changing the mode spacing (the laser repetition rate is unaffected by the AOM). Stabilization to the reference cavity uses similar modulation techniques as those used for single frequency lasers [11]. As in the continuous wave case, error signals are derived from a mixing of the reflected signal from the reference cavity, and the original modulation at 10.7 MHz. The important distinctions are that two different error signals are produced by selecting appropriate combinations of the spectrum reflected by the Fabry-Perot, and that these error signals drive combinations of actuators so as to control pulse average frequency and repetition rate independently of each other.

As shown in Fig. 11, the light reflected from the reference cavity is dispersed by a grating, and two different spectral regions are detected on two separate photodetectors. One of the photodiodes ($PD1$) provides an error signal for locking the average frequency of the fs comb. It is a composite signal of the laser frequency comb with its sidebands, and the longitudinal modes of the reference cavity, in the selected frequency range. Because of the dispersion of the reference cavity (its modes are not exactly equally spaced), better discrimination is obtained by selecting a portion of the spectrum, than by using the full spectrum. This error signal will be zero when the regular comb from the laser has a maximum overlap with the longitudinal modes of the reference cavity, in that spectral range (i.e., the *average* frequency of the laser matches the reference cavity modes) [10].

Fluctuations in the laser repetition rate result in "mode breathing." An amplified measurement of mode breathing is obtained by measuring the difference between the signals at two opposite ends of the laser spectrum, that is the difference between the signals from $PD1$ and $PD2$. By this technique, we are effectively locking the $> 100,000^{\text{th}}$ harmonic of the pulse repetition rate to the reference cavity. Such an extremely sensitive discriminator may allow the high relative stability

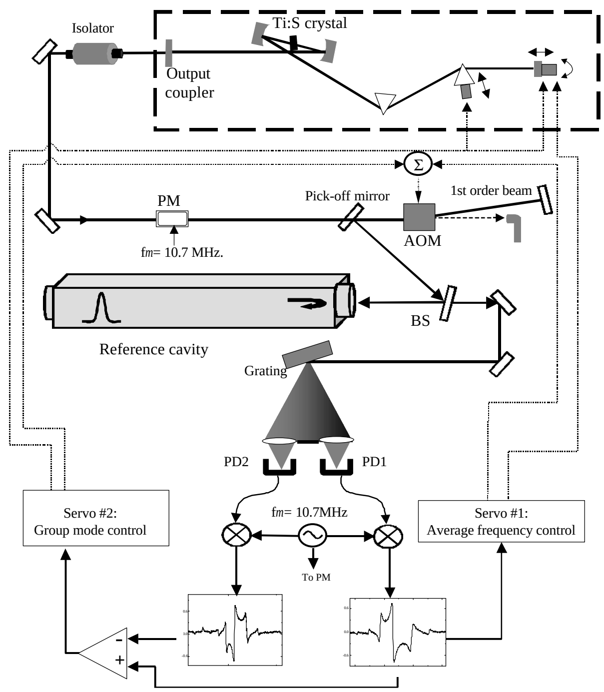

Figure 11: Schematic of the stabilization of the mode-locked laser.

of the optical transitions, $\Delta\nu/\nu$, to be transferred to the radio frequencies, $\Delta f_{rep}/f_{rep}$, when the average frequency separation of $PD1$ and $PD2$ approaches an octave. Current techniques stabilize the repetition rate, or one of its harmonic, to an electronic oscillator, and are therefore limited to the highest speed achievable by fast electronics. In the technique presented here, the phase sensitivity of the discriminator is greatly improved by a differential measurement that spans tens of terahertz, rather than gigahertz. The discrimination could be further enhanced, using newly developed specialty fibers that can extend the bandwidth of mode-locked lasers beyond an octave [12].

The average frequency of the laser is first stabilized by sending the error signal from servo #1 to the AOM for fast control of the position of the fs comb without affecting its mode spacing. Two piezo-electric transducers (PZTs) are attached to the laser cavity end mirror to provide control of the cavity length via translation ($PZT1$) and control of the average group velocity of the pulse by tilting the end mirror ($PZT2$) as first demonstrated by Reichert and others [13]. A third PZT can be used to translate an intra-cavity prism ($PZT3$) for further control of the laser cavity dispersion. Several different combinations of these actuators have been studied. The Servo 2 correction of repetition rate is applied as a linear combination of signals to the cavity length ($PZT1$) and AOM, in a manner to modify only the mode spacing without affecting the absolute position of the fs comb. This choice of actuators is advantageous as it allows a larger bandwidth to be used in stabilizing the pulse repetition frequency, since the end mirror can be translated much faster than it can be tilted. The end mirror tilt control ($PZT2$) is still used for slow corrections with large amplitude, of the pulse repetition frequency.

To measure the stability of the fs comb relative to the reference cavity, we lock a CW Ti:sapphire laser simultaneously to a single mode (which we select) of the same ULE reference cavity. A beatnote between the CW laser and modes from the fs comb is observed by mixing the beams from each laser on a fast avalanche photodiode. Figure 12 shows the beating between the CW laser and

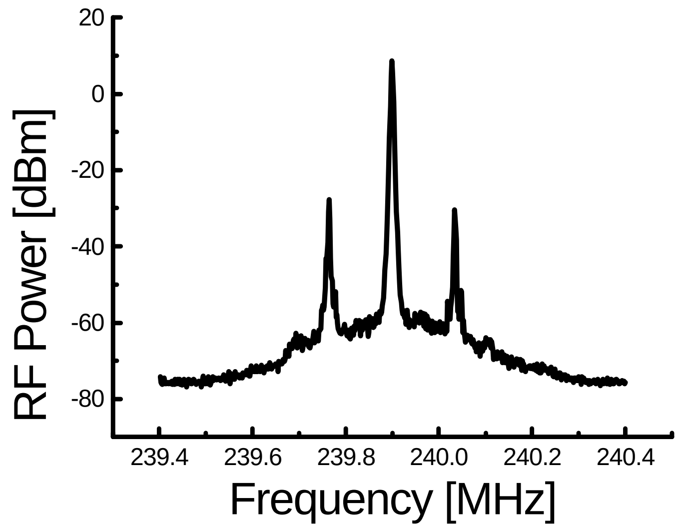

Figure 12: Beating between CW laser and one mode of the fs comb.

the $m+1$ and $m-14$ modes of the fs comb, where m is the mode of the fs comb nearest to the CW frequency. The large central peak corresponds to the laser repetition rate. The beatnote shows a $<$10 kHz linewidth (3dB) and a signal-to-noise ratio of $>$45 dB. After slight amplification through a low pass filter, the low frequency beatnote was directly counted on an HP5345 frequency counter. The calculated fractional Allan deviation from these counts is shown in Fig. 13 for a gate time of 0.10 seconds and 1000 collected samples. The instability between the two optical frequencies is as low as 2.6×10^{-12} in 1 second.

3.3 Conclusion on the mode-locked laser stabilization

Without stabilization, differential phase shifts as small as 10^{-7} are easily measured. The stabilization scheme described here should improve this figure by roughly the same amount as the laser (mode bandwidth) is narrowed, thus making measurements of differential phase shift of 10^{-10} practical. This stabilization is thus an essential step in the development of the proposed ultrasensitive magnetometers. We have developed the optical and electronics techniques to stabilize a linear fs Ti:sapphire laser. The techniques apply as well to ring lasers at any wavelength. It is an essential accessory to the ultrasensitive ring laser magnetometer. The next step, which is presently being pursued, is the long-term stabilization of the reference cavity to an atomic vapor, and the implementation of these techniques in a ring cavity.

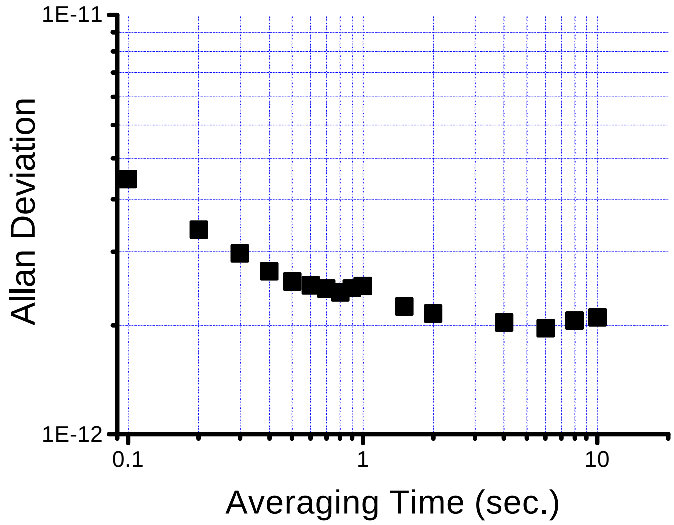

Figure 13: Allan deviation of beatnote between CW laser and fs comb.

4 Optical parametric oscillator implementation

4.1 Cavity configuration

The previous research has been conducted with a Ti:sapphire mode-locked laser, which is the laser most commonly used for research with ultrashort pulses. However, as a ring laser sensor, a Ti:sapphire laser with an intracavity saturable absorber jet is not a practical device for applications. A synchronously pumped optical parametric oscillator (OPO) (Fig. 14) is an attractive alternative. It offers the possibility to decouple relative phase and repetition rates of the oscillating signals, without the need for any moving element. The position of the crossing point of two counterpropagating trains is simply determined by optical delay lines, rather than by a saturable absorber [5] or a nonlinear crystal [14]. The mode frequencies are still set by the cavity. Another advantage is the tunability, which is important for detecting ultra-low magnetic fields, where the laser radiation has to be tuned to a narrow atomic transition.

A mode-locked Ti:sapphire laser, operating at 790 nm, is used to pump the ring OPO bidirectionally, with pulses of 175 fs duration at a repetition rate of 110 MHz. The pump laser can provide 1 W of average power in a linear configuration. The isolation between OPO and pump, provided by a single stage Faraday rotator, was marginal in the case of a linear pump laser. Therefore, a preferred configuration was with the pump in a unidirectional ring configuration, less sensitive to feedback, which provided an average power of only 400 mW. The pump beam is split into two parts that are sent in opposite directions into a 0.8-mm-long OPO crystal - periodically poled $LiNbO_3$ (PPLN) with a period of 19.75 μm. The crystal is temperature stabilized at 373°K to prevent photo-refractive damage, and achieve quasi-phase matching condition for generation of a signal around 1.4 μm.

Two outputs corresponding to opposite circulation in the OPO cavity are appropriately delayed respective to each other, before being recombined on a InGaAs photodiode collecting the interfering signals.

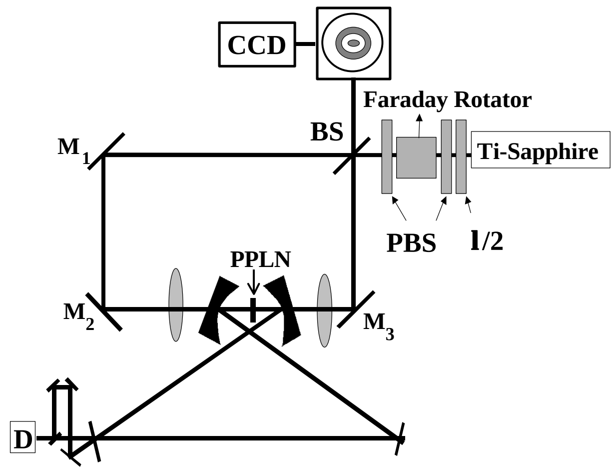

Figure 14: Sketch of the OPO cavity pumped by the Ti:sapphire laser. The reflected and transmitted parts of the beam splitter BS are focused into the PPLN crystal via the mirrors M_1 — M_2 and mirror M_3, respectively. The difference between the two optical paths determine the crossing point of the signal pulses in the OPO cavity. The two output pulses are made to interfere on a detector D after an optical delay line brings them in coincidence. In exact alignment, the mirrors BS, M_1, M_2, and M_3 constitute an antiresonant ring, the output of which can be monitored with a CCD. Since the antiresonant ring has a 100% reflection, an optical isolator, consisting in a Faraday rotator between two polarizers, is needed to protect the oscillator from the feedback.

4.2 Characteristics of the OPO ring laser

As compared to a laser, the OPO ring presents peculiar characteristics that will be detailed below, namely, (i) sensitivity to the pump focal spot, (ii) feedback to the pump laser, and (iii) cavity length tuning.

In a conventional laser, the two oppositely propagating waves experience the same gain medium. Therefore, the two counter-rotating beams are operating on the same transverse mode. In the case of the OPO, the gain volume is the focal spot of two independent beams, which have to coincide. A minor displacement of one of the pump spots results in a large change in beat signal. This spurious beat note is minimized if the two counterpropagating pumps are exactly collinear, which implies that the cavity consisting in the beam splitter BS and the three turning mirrors M_1, M_2 and M_3 is an antiresonant ring [15, 16]. The alignment of the pump is optimized by monitoring the output of the antiresonant ring. Since the antiresonant ring reflects into the laser, the pump laser should be isolated to maintain mode-locked operation. The 10^{-4} isolation provided by a single stage isolator is not sufficient to ensure stable continuous operation when the pump laser is in a linear configuration. Continuous mode-locked operation can be maintained with the Ti:sapphire laser modified into a ring configuration with four intracavity prisms, operating in unidirectional mode.

One might wonder as to whether a Sagnac effect in the antiresonant ring might alter the gyro response of the OPO. It should be remembered that the phase of the pump and that of the OPO signal generated or amplified in the PPLN crystal are uncorrelated. In a frame of reference where the signal wave repeats itself *in phase* at each round-trip, its electric field at the round-trip of index m being $E_{s,m} = \mathcal{E}_{s,m} \exp(i\omega_s t)$. To a linear approximation, the signal field at the next round-trip, after amplification in the OPO crystal of index n_0, nonlinear susceptibility $\chi^{(2)}$ and length ℓ, is:

$$E_{s,m+1} = E_{s,m} + \ell \frac{\omega}{2n_0 c} \chi^{(2)} E_{p,m} E^*{}_{i,m}. \tag{6}$$

If δ_m is a random phase fluctuation of the pump at the round-trip m, the generated idler at that particular cycle will be:

$$E_{i,m} = \mathcal{E}_{p,m} e^{i\omega_p t + \delta_m} \mathcal{E}^*_{s,m} e^{-i\omega_s t} = \mathcal{E}_{p,m} \mathcal{E}^*_{s,m} e^{i\omega_i t + \delta_m} \tag{7}$$

Inserting Eq. (7) in the generation term of Eq. (6), we find that indeed, the phase factor of the gain factor is independent of δ_m.

As previously reported [17], the signal and idler wavelengths show a very strong dependence on cavity detuning. This dependence is attributed to the group velocity dispersion of the crystal: as the cavity length is changed, another signal wavelength will have the same round-trip frequency as the pump pulses. A change of 26 μm in cavity length is sufficient to shift the signal frequency by an amount equal to its bandwidth. This sensitivity results in amplitude fluctuations of the signal of the order of 30%, which also affects the beat note. The bandwidth of the beat note (Fig. 15) is approximately 10 kHz. Such a large bandwidth can only be attributed to the third order

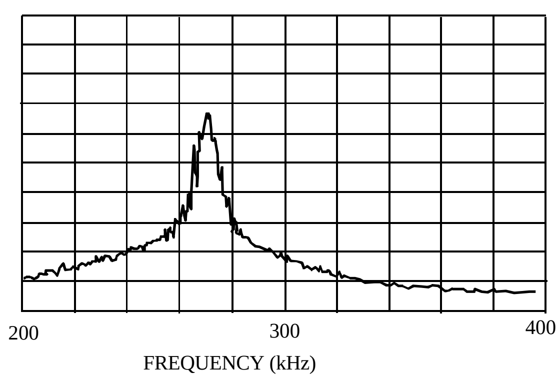

Figure 15: Spectrum of the beat note as observed by a spectrum analyzer. The vertical scale is 10 dB/div.

nonlinearity of the $LiNbO_3$ crystal, which is the only intracavity element. Indeed, the amplitude fluctuations of the signal causes differential phase shifts between counterpropagating beams. If I_+ is the peak intensity of the clockwise circulating pulse in the OPO cavity, and I_- that of the counterclockwise, the nonlinear index n_2 of lithium niobate causes a beat note frequency $\Delta\nu_{NL}$ equal to:

$$\Delta\nu_{NL} = n_2 \left(I_+ - I_- \right). \tag{8}$$

Stable operation of the OPO as a ring laser gyro will thus require active stabilization of the OPO cavity to that of the pump.

4.3 Conclusion on the OPO

We have demonstrated that the synchronously pumped OPO does indeed have potential for metrological application, and have a beat note response without dead band. However, the bandwidth of the beat note was too large for practical application. The noise in the beat note is caused by very large amplitude fluctuations of the laser, in turn a result of random cavity mismatch between the pump laser and the OPO. We are presently designing a feedback loop that locks the cavity length of the Ti:sapphire laser to that of the OPO. This will eliminate the random synchronization error between the two lasers, which is the cause of the large amplitude instabilities. Once the performances of the OPO as a sensor have been established, the next development step will be the use of a diode pumped laser — for instance a Nd:YAG or a Nd:vanadate — as a pump laser.

5 Diode pumped-solid state laser implementation

The investigation reported in the previous sections pertained to short-pulse lasers of which the backbone existed in our laboratories, but which are costly and difficult to package and use in the field. In this and the following section, we report on two laser systems that can be packaged, miniaturized, and have small power consumption: the diode pumped solid-state laser and the fiber laser. Of the two, the diode pumped laser is the most economical and closest to yield a commercial product. It is neither necessary for the laser to be high power, nor to be femtosecond. It is, in fact, desirable to have the minimum possible power and the longest pulse duration compatible with the condition that the crossing region of the pulses never overlaps with any optical component. We chose, therefore, to develop low-power ring lasers based on Nd:vanadate crystals, pumped by high brightness (gains region shorter than 200 μm) diode lasers operating at 808 nm.

5.1 Initial attempt using an intracavity MQW

Our first design, as sketched in Fig. 16 utilizes an intracavity multiple quantum well (MQW) saturable absorber as a mode-locking element.

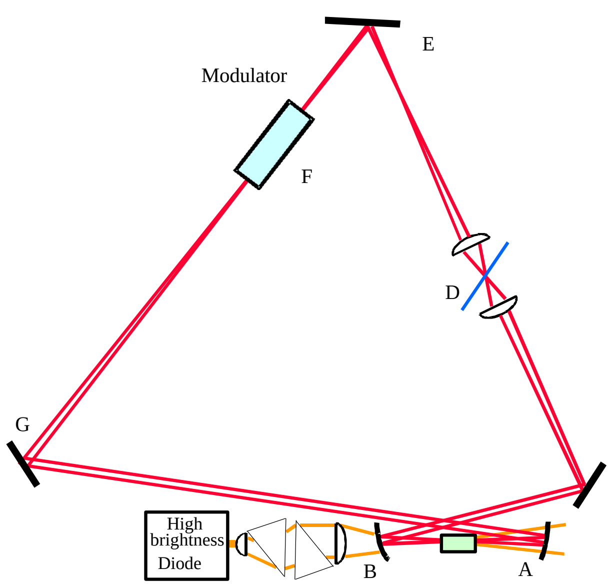

Figure 16: Small semiconductor laser pumped ring laser. The laser material is a Nd:vanadate crystal pumped longitudinally by a 2 W "high brightness" laser diode. Mode-locking is made by the saturable absorber, which is a multiple quantum well. Two 18 mm focal length lenses are used to focus the laser light into the MQW sample placed at Brewster angle. The mirrors around the gain medium A and B have a radius of curvature of 5 cm.

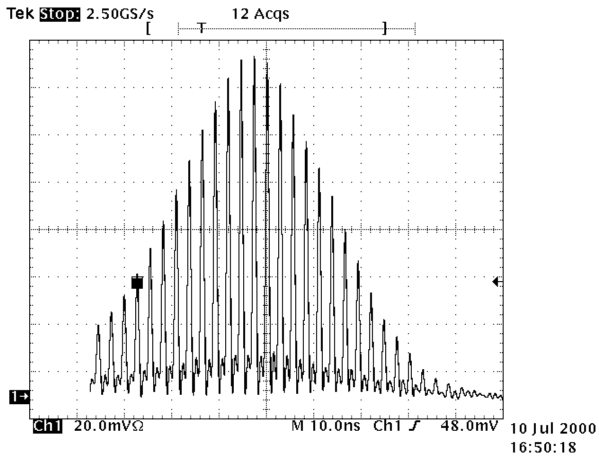

Figure 17: Q-switched-mode-locked output of the laser sketched in Fig. 16.

The saturable absorber consists of a 0.5 mm thickness substrate, on which 10 pairs of layers were grown, each pair consisting of an absorbing layer of $In_{0.25}Ga_{0.75}As$, 8 nm thickness, and a spacer layer of GaAs, 65 nm thickness. The MQW were grown at low temperature (630 to 680°K) by MBE at the Center for High Technology Material (CHTM). These samples were annealed either at 350°K, 500°K or 600°K. Only continuous operation of the laser is observed with the samples annealed at the two higher temperatures. For the sample annealed at the lowest temperature (350°K), the output consists in a train of macropulses at a few microseconds interval, instead of continuous mode-locked operation. Each of these microsecond-long bursts, as shown in Fig. 17, consists of a short train of mode-locked pulses. The operation of the laser is bidirectional and it should be possible to detect a beat note. A continuous operation would however be preferable. Therefore, numerical modeling and calculations were made to determine which parameter should be modified to achieve unidirectional operation. One of the solutions that emerged from the theory was to reduce the linear losses as well as the modulation depth through the saturable absorber, and increase the saturation intensity. These changes resulted in the cavity of Fig. 18,

5.2 Use of a saturable absorber in reflection

Instead of a multiple quantum well used in transmission, five quantum well layers were grown on a reflector. The substrate is still a 0.5 mm thickness wafer of GaAs polished on both sides. The mirror structure consists in 25 pairs of alternating layers of GaAs (75.8 nm) and AlAs (89.9 nm). The five quantum well layers are 8.7 nm thick ($In_{0.25}Ga_{0.75}As$) spaced by 10 nm of GaAs. The five last pairs of layers are low temperature (350°C) grown by MBE.

In this configuration, continuous mode-locking is observed. An oscilloscope trace of the pulse train is shown in Fig. 19. The cavity period is 2.6 ns.

The interfering pulse train shows a small beat signal at 25 Hz (Fig. 19 right) that could not yet be positively identified. One possibility is that it is due to a mechanical vibration resonance of the thin MWQ sample. It does, however, appear that the two modes of the laser are locked to each other, which is to be expected because of the scattering of the MQW sample.

The alignment is presently too critical for motional dithering (moving the MQW transverse to the beam) to be practical. Electro-optical dithering nonetheless can be implemented. To this effect, a 0.5 mm sample of $LiNbO_3$ is inserted in the cavity as shown in Fig. 18. The amplified plus train is applied to that sample, following the arrangement sketched in Fig. 5. Two examples

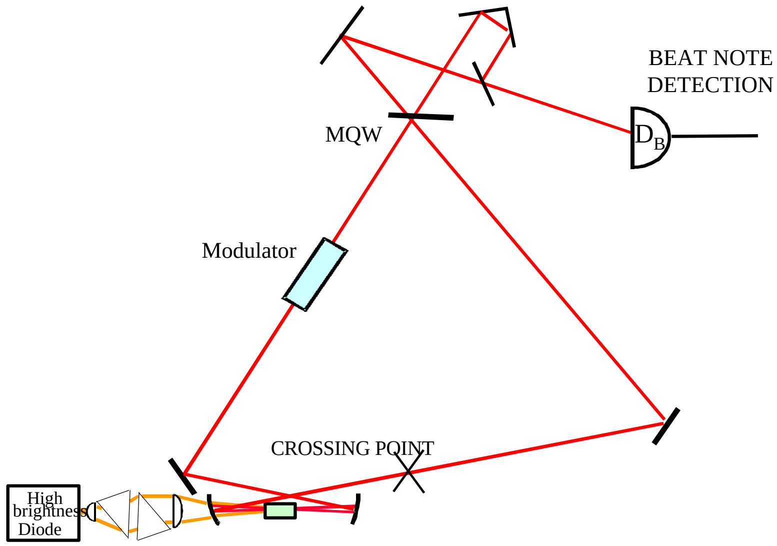

Figure 18: Second configuration of the semiconductor laser pumped ring laser, using a reflecting saturable absorber. Mode-locking is made by the MQW saturable absorber grown on top of a stack of reflecting layers. The two outputs are taken through the MQW mirror, and given appropriate relative delays as to interfere on a photo diode and produce the beat note.

of beat notes are shown in Fig. 20.

The beat note is then observed to be sinusoidal, and vary linearly with the voltage applied to the lithium niobate, for voltages in excess of 8V (beat note of 8 kHz). At lower voltages, the beat note waveform is distorted, indicating the proximity of a dead band, as shown on the right of Fig. 20. The dead band is at a frequency of approximately 2 kHz.

An autocorrelation measurement shows the pulse duration to be approximately 70 ps. This value is twice the value that is expected for this type of laser. This long-pulse duration can be the cause of the relatively large lock-in frequency (2 kHz) that is observed. Indeed, the crossing points for the pulses in the cavity are at the saturable absorber mirror, and at the point marked by a cross on Fig. 18. The latter crossing point is only 3 cm away from the curved mirror. Therefore, partial overlap of the pulses occur on that mirror, which could explain the large dead band. The unusually large pulse duration can be due to a Fabry-Perot effect of the Nd:vanadate crystal, which may have been oriented too close to the normal to the intracavity beam. Another possible cause for the longer pulse duration may be the non-optimized MQW mirror. Further efforts are presently being made to reduce the pulse duration and the lock-in frequency. While the dead band can be suppressed electronically, the smaller the lock-in frequency, the smaller the power required for the electronics needed for the electro-optic dithering.

5.3 Conclusion on the diode laser pumped solid-state laser

For the short term, the diode pumped laser is by far the most promising approach. We have demonstrated bidirectional, mode-locked operation. The relatively long pulses and large dead band observed are not of significant concern, since we have demonstrated elimination of the dead band by electro-optic dithering. Some design and electronics optimization remains to be done to turn this laser into a practical sensor.

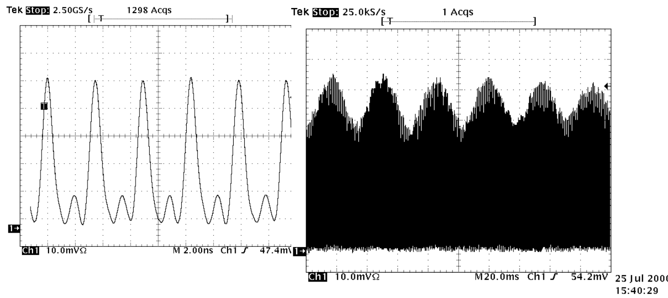

Figure 19: Pulse train from the semiconductor laser shown in Fig. 18. Left: scale of 2 ns/div. Right: 20 ms/div.

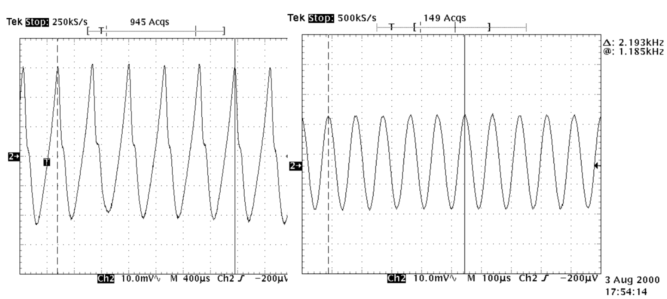

Figure 20: Beat note from the semiconductor laser shown in Fig. 18, with electro-optic dithering. Left: scale of 400 μs/div. Right: 100 μs/div.

6 Fiber laser implementation

There are many advantages to fiber lasers, not the least of which is the ease of alignment and potential portability. An obvious advantage is that they do not require any bulk optical component and the associate hardware (mirror mounts, positioners, translation stages). The research phase is particularly costly and tedious because the sensitivity of the fibers to the environment (temperature, acoustic perturbations, even air currents). For our applications, one of the major issues to be resolved is the stability of the modelocked operation.

However, the fibers are the only option possible for making an ultrasensitive sensor of magnetic susceptibility, because the cavity round-trip time can be extended to the microsecond scale.

6.1 The sigma laser

We report here on the development of a short-pulse bidirectional femtosecond laser to be used as an ultrasensitive sensor for low frequency applications. The laser is configured as the Greek letter "sigma", as sketched in Fig. 21. The cavity comprises of two sections, a ~14 meter long ring portion

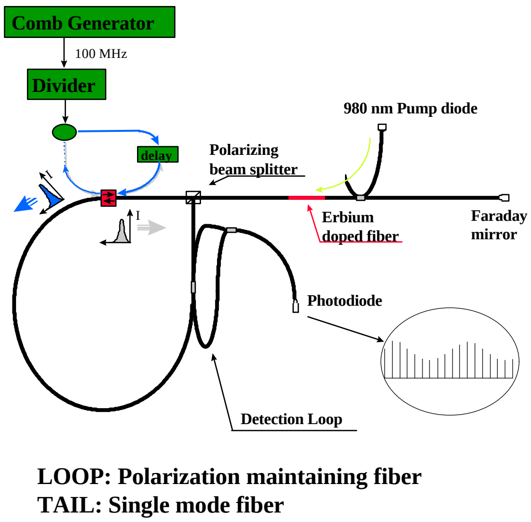

Figure 21: Sketch of the "sigma" laser cavity under development.

which senses the rotation rate and a ~100 meter long linear section where the gain medium resides. The laser configuration resembles the Greek letter σ, hence its name. The two portions are joined by a polarizing beam splitter. Cavity parameters are adjusted to maintain crossing points away from the gain region, splice joints, and various elements that are more likely to scatter light. The gain resides in the linear section of the cavity to maintain greater symmetry for all pulses. The problems arising from polarization effects are minimized by the use of a polarization maintaining (PM) fiber in the ring of the cavity. The linear section is a single mode fiber. Any depolarization that takes place within this part is compensated for by the use of a Faraday rotator mirror at the end of the linear section.

The ends of the PM section of fiber are oriented so that light is coupled into the *slow* axis of the fiber for both propagation directions. The polarizing beam splitter forces the light in each direction to start out in a different state of polarization, and the PM fiber maintains that state. Upon return to the linear section, the two beams will have opposite linear polarizations.

Bi-directional mode-locking of the laser is done with a traveling wave modulator that is able to act as a directional gate for the light. A picosecond electrical pulse generator is triggered by the optical pulse itself. The modulator is biased such that it is "closed" most of the time. An additional voltage causes the modulator to open, allowing light to pass through. Thus one can form a gate that specifies when light can circulate within the cavity by controlling the switching signal. For electrical signals shorter 100 ps, it acts as a *unidirectional gate*, allowing light to pass in one direction only. Bidirectional operation is achieved by sending an identical signal, after an appropriate delay, into the second input port such that it travels in the opposite direction. Since the operation is active modelocking, the timing jitter is determined by that of the driver for the modulator, and the duration of the electrical impulse.

The biggest challenge with this approach is that the opening time of the travelling wave gate is only a few picoseconds. The timing jitter for the opening of this gate cannot be more than several picoseconds, which is a very difficult condition to achieve at a MHz round-trip time. The frequency source used to modelock the laser has to be locked to the cavity repetition rate or else the two will drift apart. Typically, this process is a thermal one. Changes in ambient temperature changes the

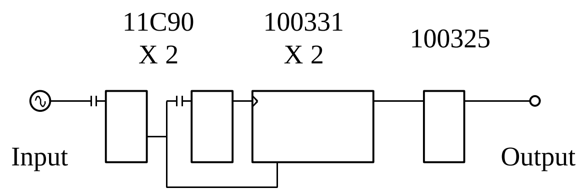

Figure 22: The frequency division circuit. An RF sinusoidal waveform is capacitively coupled to the input. A square wave TTL signal is the output. The first two IC's are Fairchild's 11C90 prescalers (obsolete) each set to ÷11, followed by four D-type Flip-Flops National's 100331) to achieve a further ÷4. The resulting ECL signal is converted to TTL via a translator (National 100325) and sent to the PPL impulse generator to drive the MZM.

cavity length (thermal coefficient of optical fiber $\approx 10^{-5}/^{o}$C). Likewise, the oscillator (even a good crystal) would also have some temperature drift associated with it. Also, stable crystals tend to be of fixed frequency, which makes them much harder to use when the cavity rate cannot be held constant.

The "Picosecond Pulse" generator 3500D to drive the modulator utilizes a pair of tunnel diodes to create a fast risetime, medium voltage impulse. The resulting waveform has a nominal FWHM of 65 ps with amplitudes up to ± 9 V. The nominal RMS jitter of the device is 1.5 ps with respect to the *trigger signal*. These diodes require some recovery time between switching and therefore cannot be used at frequencies above 1 MHz. Aside from this limit, the internal frequency source is a TTL circuit whose jitter was measured to be in the 400ps range and can drift quite a bit due to the RC time constant of the oscillator. Note that the risetime of TTL signals is in the few ns range. An external adjustable source was available to trigger the impulse generator. To reduce the jitter associated with the 1 MHz signal, it was decided to start with a higher cavity harmonic and divide the frequency down to the correct value. ECL technology with risetime of 1 ns or less had to be used to alleviate the electronics jitter. Motorola has a family of chips called ECLinPS capable of risetimes in the 100's ps.

The faster risetimes come at a cost of greater coupling between signals and EMI. It was possible to drive the MZM using the PPL impulse generator triggered with a sine wave at 484 times the cavity repetition rate and achieve stable pulses. The schematic for the divider circuit is shown in Fig. 22. However, ECL is also much more prone to failure due to numerous causes, the greatest of which is the user unfamiliarity with the logic family. In addition, the semicondutor industry is moving more and more toward bulk assembly manufacturing and surface mounted technology (SMT). The older chip series were phased out in favor of miniaturized models, making it much harder to do prototype work without investing in specialized equipment. The combination of more delicate ICs and unavailability of robust, older ICs was a great impediment to rebuilding a second circuit that could trigger the PPL generator. A second, more catastrophic, occurrence (destruction of the travelling wave modulator) resulted in our decision to try passive modelocking with an eye toward a hybrid system in the future.

6.2 Hybrid mode-locking

Our new approach is to rely on nonlinear effects in the fiber to create the pulses by passive mode-locking, and to use a pair of modulators, properly timed, to control the synchronization and directionality of the pulses.

The passive modelocking method relies upon nonlinear polarization rotation to maintain pulsed operation. Under some circumstances it is possible to get the pulsing to self-start. Currently, the laser is restricted to unidirectional operation by splicing an isolator into the cavity before the gain region. The laser's repetition rate is around 7 MHz, and the pulse duration around 500 fs. The isolator is now being replaced by the pair of modulators, which have the same function as the isolator, but can let pulses evolve alternatively in either direction.

6.3 Conclusion on the Fiber laser approach

With cavity length that can be hundreds of meters, fiber lasers offer unique possibilities in the area of detection of minute and remote changes in magnetic susceptibility. Progress is slow and difficult since this is still an area of basic research. We expect to have a laboratory demonstration of a fiber sensor within one year, using the bidirectional mode-locked fiber lasers.

7 Synopsis

This report presents the results of a feasibility study to apply femtosecond lasers to the detection of magnetic susceptibility or the detection of minute changes in magnetic field. The purpose of the measurement is the detection of underground water sources. The basic idea in the detection scheme is to use a ring laser as a differential interferometer. A change in magnetic susceptibility, or a change in magnetic field, is converted in a change in optical perimeter P seen by the two counter-propagating beams in a bi-directional mode-locked ring laser. This difference in perimeter ΔP ($\ll P$) is measured as a beating between two output beams of a ring laser, of frequency $\Delta\nu = \nu\Delta P/P$. Since the optical frequency ν is of the order of 10^{15} and that changes in beat frequencies $\Delta\nu$ of the order of one Herz can be measured (at the present state of this technology), the method can sense changes in optical path $\Delta P/P$ of the order of $1/10^{15}$.

We have shown in section 3 how this sensitivity can be improved by at least a factor 1,000 through stabilization. We have developed the optical and electronics techniques to stabilize a fs laser. This is an essential step in the development of the proposed ultrasensitive ring laser magnetometers. The next step is the implementation of these techniques in a ring cavity, as well as locking the laser frequency to an atomic vapor.

One attractive implementation that was reported in section 4 is the synchronously pumped OPO, for which we have demonstrated a beat note response without dead band. However, the bandwidth of the beat note was too large for practical application. The noise in the beat note is caused by very large amplitude fluctuations of the laser, in turn a result of random cavity mismatch between the pump laser and the OPO. This problem is being presently addressed by designing a feedback loop that locks the cavity length of the Ti:sapphire laser to that of the OPO. This will eliminate the random synchronization error between the two lasers, which is the cause of the large amplitude instabilities. Once the performances of the OPO as a sensor have been established, the next development step will be the use of a diode pumped laser — for instance a Nd:YAG or a Nd:vanadate — as a pump laser.

A study of the diode pumped laser has been initiated, and is reported on in section 5. We have demonstrated bidirectional, mode-locked operation. The relatively long pulses and large dead band observed are not of significant concern, since we have demonstrated elimination of the dead band by electro-optic dithering. Some design and electronics optimization remains to be done to turn this laser into a practical sensor.

To detect directly magnetic susceptibilities, averaged over long distance, a very long cavity length (of the order of several hundred meters) is required. This is still an area of basic research. The results of our preliminary attempts are reported in section 6. We have succeeded in achieving unidirectional mode-locked operation. and anticipate to produce bidirectional operation leading to a laboratory demonstration of a fiber sensor within one year.

References

[1] E. D. Gray *American Institute of Physics Handbook*. McGraw-Hill, New York, 1972.

[2] D. J. Teskey, P. J. Hood, L. W. Morley, R. A. Gibb, P. Sawatzky, M. Bower, and E. E. Ready. the aeromagnetic survey program of the geological survey of Canada: contribution to regional geological mapping and mineral exploration. *Can. J. Earth Sci.*, 30:243–260, 1993.

[3] P. J. Hood. Geophysics: the tools of the trade. *Northern Miner*, 1–14, 1991.

[4] P. J. Hood and S. H. Ward. Airborne geophysical methods. In H. E. Landsberg and J. Vann Mieghem, editors, *Advances in Geophysics*, 13: pages 1–111. Academic Press, 1969.

[5] S. Diddams, B. Atherton, and J.-C. Diels. Frequency locking and unlocking in a femtosecond ring laser with the application to intracavity phase measurements. *Applied Physics B*, 63:473–480, 1996.

[6] S. Diddams, B. Atherton, and J.-C. Diels. Differential intracavity phase spectroscopy of a three-level system in samarium. *Phys. Rev. A*, 58:2252–2263, 1998.

[7] M. J. Bohn, J.-C. Diels, and R. K. Jain. Measuring intracavity phase changes using double pulses in a linear cavity. *Optics Lett.*, 22:642–644, 1997.

[8] Th. Udem, J. Reichert, R. Holzwarth, and T.W. Hänsch. Accurate measurement of large optical frequency differences with a mode-locked laser. *Opt. Lett.*, 24:881–883, 1999.

[9] Th. Udem, J. Reichert, R. Holzwarth, and T.W. Hänsch. Absolute optical frequency measurement of the cesium D_1 line with a mode-locked laser. *Phys. Rev. Lett.*, 82:3568–3571, 1999.

[10] R. J. Jones, J. C. Diels, J. Jasapara, and W. Rudolph. Stabilization of the frequency, phase, and repetition rate of an ultra-short pulse train to a Fabry-Perot reference cavity. *Optics Comm.*, 174:409–418, 2000.

[11] K. H. Drever, J. L. Hall, F. V. Kowalski, J. Hough, G. M. Ford, A. J. Munley, and H. W. Ward. Laser phase and frequency stabilization using an optical resonator. *Appl. Phys.B*, 31:97–105, 1983.

[12] J. K. Ranka, R. S. Windeler, and A. J. Stentz. Visible continumm generaton in air-silica microsctructure optical fibers with anomalous dispersion at 800 nm. *Optics Lett.*, 25:25–27, 2000.

[13] J. Reichert, M. Neiring, R. Holzwarth, M. Weitz, Th.Udem, and T. W. Hänsch. Phase coherent vacuum-ultraviolet to radio frequency comparison with a mode-locked laser. *Phys. Rev. Lett.*, 84:3232–3235, 2000.

[14] M. J. Bohn, R. J. Jason, and J.-C. Diels. Mutual Kerr-lens mode-locking. *Opt. Comm.*, 170:85–92, 1999.

[15] Siegman. *Lasers*. University Science Books, Mill Valley, CA., 1986.

[16] N. Jamasbi, J.-C. Diels, and L. Sarger. Study of a linear femtosecond laser in passive and hybrid operation. *J. of Modern Optics*, 35:1891–1906, 1988.

[17] D. T. Reid, M. Padgett, C. McGowan, W. E. Sleat, and W. Sibbett. Light-emitting diodes as measurement devices for femtosecond laser pulses. *Optics Lett.*, 22:233–235, 1997.