# Mean-Field Laser Magnetometry

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A quasimirrorless laser is shown to exhibit large interferences between macroscopic quantum states when submitted to weak external magnetic fields. Such a device is shown to have potentialities as a high signal-to-noise ratio vectorial magnetometer, especially because of its sensitivity to the mean value of the longitudinal magnetic field and its fast response to magnetic field variations. The behavior of the laser magnetometer is in good agreement with theory.

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Measurement of weak magnetic fields is a ticklish problem that occurs in many areas of physics. Among existing magnetometers, some are based on classical effects, such as magnetic induction, classical Hall effect, or magnetostriction. On the other hand, quantum-effect-based magnetometers can be classed in two main families. First, some of them use large sets of *microscopic quantum devices* which are mainly independent of each other. This is the case for NMR [1] and optical pumping [2,3]. In such devices, each system—atom or nucleus—acts independently and the useful signal is the result of the statistical summation over the whole set of microscopic quantum systems. This leads to problems when this signal is inhomogeneous, due, for example, to a strong spatial inhomogeneity of the magnetic field to be measured. The useful signal is indeed broadened in the presence of such inhomogeneities. The second class of quantum magnetometers uses *macroscopic quantum effects* [4]. One example is the superconducting quantum interference device (SQUID) magnetometer which uses the collective behavior of electron pairs in a superconducting ring [5]. Systems that exhibit macroscopic quantum effects produce modes, i.e., coherent behavior of many elementary quantum subsystems, and interferences. The laser has already been considered a particularly striking case of a system exhibiting macroscopic quantum behavior [4,6]. One may consequently wonder whether such behavior can be used to build a sensitive and simple laser magnetometer that would not be disturbed by magnetic field gradients.

The action of a magnetic field on a laser has been extensively studied in early works about Zeeman lasers [6,7] in which the experimental setup had to be isolated from the ambient magnetic field by using Mumetal shields. These works have pointed out that the behavior of Zeeman lasers is mostly governed by the intracavity anisotropies. To avoid such complications, which are usually due to the mirror coatings [8], we have built a *quasimirrorless laser.* This laser, shown in Fig. 1(a), is built with a $L=60$ cm long Zerodur block [9]. The cavity is made with two *uncoated mirror substrates* that provide only 3% reflectivity each. The 3.39-$\mu$m transition of neon produces the high gain (up to 700 per pass) necessary to obtain the oscillation and leads to a large Faraday effect. We use a 5:1 $^3$He-$^{20}$Ne gas mixture at the total pressure $P=1.1$ Torr. One substrate is plane and the other one has a radius of curvature $R=5$ m. Under these conditions, the mode sizes are $w_R=1.41$ mm on the spherical mirror and $w_0=1.32$ mm on the plane mirror. The bore diameter (3.4 mm) is calculated to restrain any transverse mode except the $TEM_{00}$ from oscillating. Under these conditions, the laser oscillates in a single longitudinal and transverse mode for discharge currents above 5 mA in each arm. The laser output power is in the range of a few 10 $\mu$W. When the system is submitted to a weak longitudinal magnetic field like the ambient magnetic field existing inside the laboratory, the Zeeman

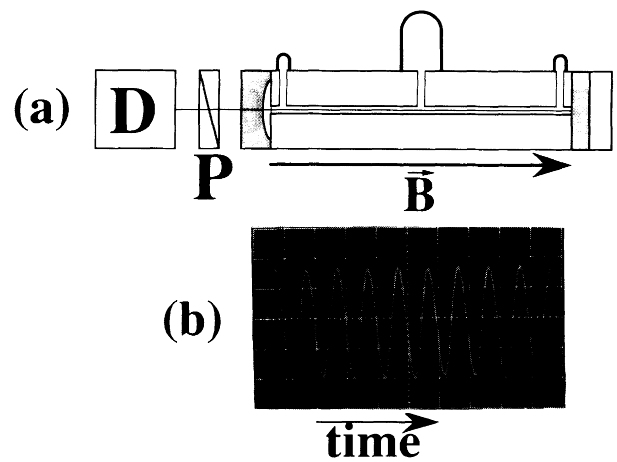


FIG. 1. (a) Schematic representation of the experimental setup. The laser is built from a block of Zerodur and the reflectors are just mirror substrates. The interferences between the two macroscopic quantum states are visualized through a linear polarizer. (b) Typical signal collected from the detector vs time (horizontal axis: 5 $\mu$s per division).

effect leads to the existence of two oppositely circularly polarized modes inside the laser. Thanks to the use of quasimirrors, there is a small amount of energy stored inside the cavity and the Faraday effect associated with the Zeeman effect is only weakly saturated. Thus, this Faraday effect is large even for weak magnetic fields and hence the two modes do not experience the same phase shift for one pass in the cavity, like the two categories of electron pairs that pass through each junction in the SQUID magnetometer [10]. In the SQUID magnetometer, which is equivalent to a Mach-Zehnder optical interferometer, the phase shift leads to magnetic-field-dependent interferences when the two arms of the interferometer are recombined. In the laser, which is a resonant device, the phase difference leads to the existence of optical beat between the two macroscopic modes. This beat is detected through an optical isolator and a linear polarizer that play the role of the recombination stripe in the SQUID. The typical evolution of the signal versus time is shown in Fig. 1(b) when the laser axis is parallel to the horizontal component of the Earth's magnetic field. This optical beat between the two opposite circularly polarized modes is equivalent to the periodic rotation of a linearly polarized mode and leads to a high signal-to-noise ratio.

Let us now study the evolution of the observed beat frequency with the longitudinal magnetic field. The polarization is submitted to the competition between two effects: the Faraday effect that makes the linear polarization rotate periodically and the eventual residual small anisotropies of the quasimirrors that make the linear polarization stable. We consequently expect the system to exhibit a typical Adler-type dynamics [11,12] with a narrow locking region $B_c$. The observed frequency $f$ must then obey the equation

$$f=K(B^2-B_c^2)^{1/2}, \tag{1}$$

where $B=(1/L)\int_{-L/2}^{L/2}B_z\,dz$ is the mean value of the longitudinal magnetic field along the laser axis $z$, and $K$ is a proportionality factor that depends on the characteristics of the laser, the excitation level, and the detuning. We introduce the laser inside a 1-m-long solenoid and observe the beat frequency versus magnetic field. The experimental measurements are represented by points in Fig. 2. The agreement between the theoretical curve deduced from (1) and the experimental measurements (see Fig. 2) shows that our predictions are valid and that the small locking region is equal to a few milligauss. For values of the mean magnetic field outside this locking region or by biasing the value of the applied magnetic field, the observed beat frequency evolves linearly with the longitudinal magnetic field, showing that $K$ does not depend on $B$. The narrow locking region is due to the residual anisotropies of the reflecting interfaces that can be caused by residual tensile stresses inside substrates and could be reduced by the use of a more appropriate unstressed material.

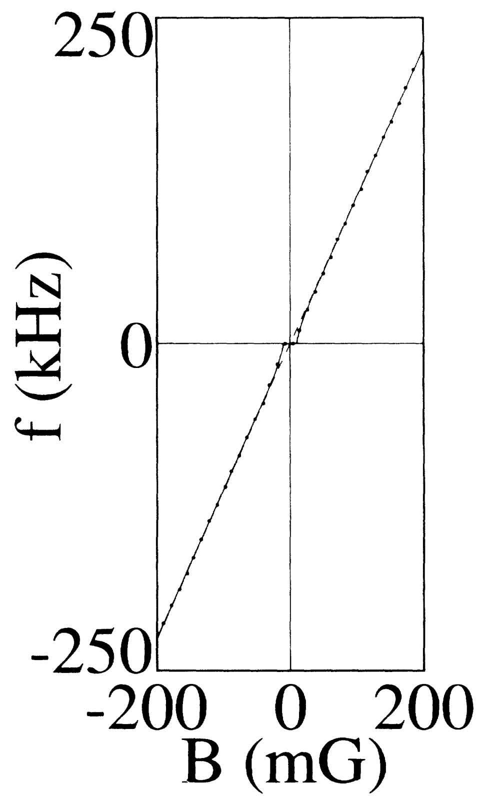


FIG. 2. Observed beat frequency $f$ vs mean externally applied longitudinal magnetic field $B$. The points are experimental data and the full line is the corresponding theoretical Adler curve obtained from Eq. (1). Notice the narrow locking region around $B=0$.

Many applications, like for instance seismology, require the measurement of rapid variations of the magnetic field. Another interesting potentiality of the laser magnetometry is its ability to detect such fast variations of the applied magnetic field. Because of the very low finesse of the cavity, the lifetime of the photons in the quasimirrorless cavity is very low (a few nanoseconds), of the same order as the atomic variables lifetime. Consequently, the bandwidth of the system will only be limited by the value of the carrier frequency. This carrier frequency is about 200 kHz when the device is submitted to the horizontal component of the Earth's magnetic field (about 200 mG), like that shown in Fig. 1(b). Thanks to an extra wire perpendicular to the laser axis, a square modulation is added to the Earth's magnetic field. The peak-to-peak modulation amplitude averaged along the laser length is 1 mG. The output signal is analyzed through a Hewlett-Packard HP 53310A modulation domain analyzer that gives the evolution of the frequency of the optical beat versus time. The result is given in Fig. 3, which shows that the rise time of the system is about 100 $\mu$s.

One of the most inconvenient limitations of mi-

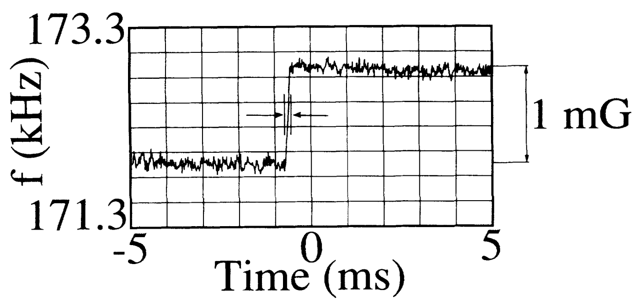


FIG. 3. Observed beat frequency $f$ vs time when a square modulation is added to the external magnetic field (modulation amplitude 1 mG).

croscopic-quantum-effect-based magnetometers is their inability to operate in highly perturbated magnetic environments, like, for example, spatially inhomogeneous magnetic fields. We performed all the experiments in a non-magnetic-shielded room and without any Mumetal shield around the experimental setup. For these conditions, a typical proton NMR magnetometer was unable to measure the value of the ambient magnetic field, in contrast to the laser magnetometer. The latter is indeed only sensitive to the mean value of the longitudinal magnetic field, because its macroscopic modes average the field along the cavity. This feature is illustrated by the following experiment: A weak sinusoidal modulation at 0.2 Hz is superimposed to the external magnetic field. Although the laser magnetometer is submitted to important spatial and time variations of the ambient magnetic field (several mG), one can still clearly discern the extra modulation when its peak-to-peak amplitude is equal to 100 $\mu$G, as shown in Fig. 4(a), and even to 10 $\mu$G (1 $\gamma$, i.e., 1 nT), as shown in Fig. 4(b). Such variations represent a few parts in $10^5$ of the mean magnetic field and are in agreement with the predicted theoretical modulations.

For magnetic-field-measurement applications, one may wonder what the long-term stability of the observed frequency in a constant environment is. The scale factor $K$ of Eq. (1) indeed depends on the optical frequency and the intensity of the laser. However, measurements of these variations on the present device show that a 10 ppm stability of $K$ can be obtained if the laser intensity is stable at $10^{-4}$ and the optical frequency at $10^{-9}$. Such stabilities are commonly achievable with the usual techniques for ultrastable Zerodur structures, for example, by stabilizing the discharge current and locking the cavity length so that the laser remains at the maximum of the output power versus cavity length profile. Besides, the problem of the locking field $B_c$ can be circumvented by applying to the magnetometer an extra sinusoidal magnetic field that can be provided by a sinusoidal current in a wire. Moreover, if this extra sinusoidal magnetic field is well calibrated, it can also provide a means of controlling the variations of the scale factor $K$. With such techniques, our measurements show that a precision better than 1 $\gamma$ can be achieved for magnetic fields of the order of magnitude of the Earth's magnetic field.

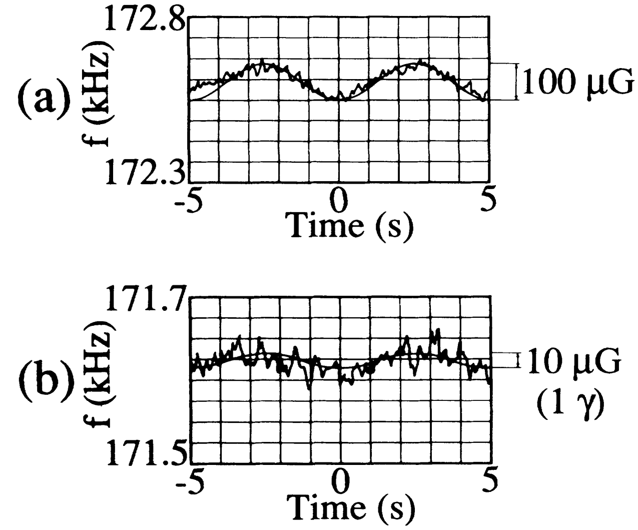


FIG. 4. Observed beat frequency $f$ vs time when a sinusoidal modulation at 0.2 Hz is added to the ambient magnetic field. The full-line sinusoids are the corresponding theoretical curves. (a) Modulation amplitude: 100 $\mu$G. (b) Modulation amplitude: 10 $\mu\text{G}=1\ \gamma$.

In conclusion, we have shown that the behavior of a quasimirrorless laser in an external magnetic field is a good illustration of interference effects between macroscopic quantum effects or modes. The macroscopic modes of such a device exhibit interferences that depend on the mean value of the component of the magnetic field that is parallel to the laser axis. This allows one to use such a device as a vectorial mean-magnetic-field sensor in extreme conditions. We have indeed shown that the laser magnetometer can be sensitive to variations of the mean external magnetic field of 10 $\mu$G (1 $\gamma$) without any data processing, even in an environment where spatial inhomogeneities of the magnetic field are so large that usual microscopic-quantum-effect-based magnetometers such as NMR magnetometers are unusable. Moreover, such a system exhibits a fast response to magnetic field changes with rise times as short as 100 $\mu$s. Such characteristics could lead to possible applications in geophysics, seismology, volcanology, and prospecting. This work is an example of the introduction of quantum optics in the realm of precision magnetometry, as recently predicted in a different manner [13].

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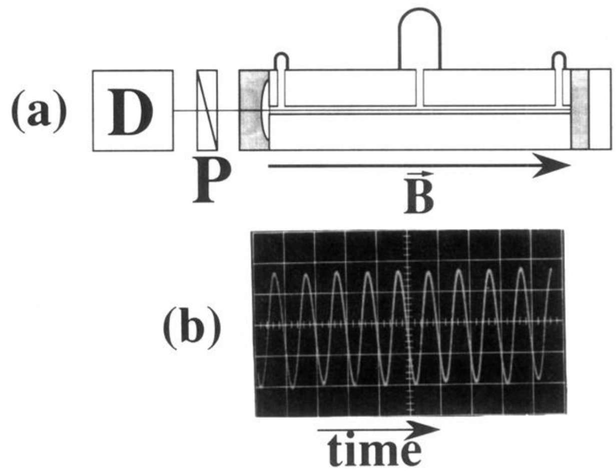


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