The development of optical quantum magnetometry dates back to the 1940s, when it originated from the works of Bloch [1] and Kastler [2]. The application of lasers to the tasks of magnetic resonance optical pumping and detection has resulted in the development of various magnetometric systems using substantially new principles. In comparison to these systems, magnetometric sensors [3] that use ‘classical’ optically detected magnetic resonance with or without laser pumping may be characterized as ‘classical quantum’ optically pumped magnetometers (CQOPMs). Recently developed modifications of CQOPMs have proven their ability to demonstrate absolutely new features or new combinations of features.

There are two ‘classical’ ways to detect magnetic resonance. The most obvious way is to detect the population difference, or the MZ component of magnetic moment using light beam \( L_z \) parallel to the magnetic field \( B \) (see figure 1). This MZ component is quite symmetrical and the corresponding line center position is stable, but it is slow; its dynamics is limited by the relaxation time \( T_1 \), and its observation requires frequency modulation. Another way is detection of the rotating transverse component of the magnetic moment using transverse light \( L_x \). The resonance detected this way is called MX resonance, and the devices that use it are MX magnetometers. They are much faster and they do not need any modulation; they lock directly to the zero point of the phase-detected resonance line. Their drawback is lower accuracy, because the zero point position depends on many factors such as the phase of the signal detection.

For a long time the potassium optically pumped MX magnetometer (MX-POPM) demonstrated the most impressive combination of time response, short-term resolution, and stability among all the devices suitable for measuring geomagnetic fields [4]. However, even though the MX-POPM accuracy exceeds the accuracy of Cs magnetometer by two orders of magnitude, it is still two orders of magnitude lower compared with the potential accuracy of potassium MZ magnetometer (MZ-POPM); the main reason for this is the MX signal phase determination error. Another factor that limits the accuracy of the MX-POPM is the presence of more than one resonant transition in the Zeeman spectrum of alkaline atoms. For the MX-type signal, the influence of the adjacent resonance on the position of the selected resonance line is characterized by the value of

\[
\frac{\alpha}{\Gamma^2} \left| \frac{\Delta}{\Gamma} \right|
\]

where \( \Gamma \) is the half-width of the magnetic resonance line, \( \alpha < 1 \) is the relative magnitude of the adjacent resonance, and \( \Delta \) is the distance to the adjacent line (\( \Delta >> \Gamma \)). For the MZ-type signal, the influence of the adjacent resonance is much smaller because it is proportional to \( \Gamma^2/\Delta^3 \).

Recently, we have developed a prototype of a magnetometer that combines the advantages of these MX and MZ devices using a single sensor and the classical MX pumping scheme [5]. This device uses two different kinds of magnetic resonance signal at the same time: (i) the ordinary MX signal [3] proportional to the instant value of the projection of the rotating magnetic moment \( M \) to the \( x \) axis and (ii) a relatively slow MR signal proportional to the amplitude of the transverse, i.e., rotating in \( \theta xy \) plane, component of \( M \).
A K Vershovskii et al

In this scheme the total magnetic field vector component magnetometer was suggested as an extension of time responses can be obtained. The idea of an absolute three-dimensional total field module to be retained and therefore much faster sections; the prototype device showed a response speed of 10 readings per second at a reproducibility of measurements at a level of 2 to 3 pT rms [5].

Various methods of measuring components of the magnetic field with scalar sensors placed in an auxiliary field system are widely known. Two devices using this principle K and Cs vector variometers have been described [6, 7]. Although all the known devices used fast switching of the auxiliary field direction, these devices use rotating auxiliary fields, which allow the total field module to be retained and therefore much faster time responses can be obtained. The idea of an absolute three-component magnetometer was suggested as an extension of these projects. In this scheme the total magnetic field vector in the sensor rotates around the initial field direction, retaining its length. In each rotation cycle it passes through the three positions such that in each position two components of the measured magnetic field are compensated with high accuracy, whereas the third one is fully uncompensated and amenable to measurement [8]. The method was justified mathematically; it shows an absolute vector accuracy of the order of 0.1 nT for a measuring time of 0.1 s. The short-term sensitivity of the measurements is determined by the sensitivity of the Mx magnetometer.

In the 1970s, projects involving use of Mx signal angular dependencies for direct vector measurements started to appear. The amplitude of a magnetic resonance shows a dependence on the direction of the pumping and probe beams; however, this dependence is, in itself, too weak to be used. A more promising possibility was discovered by Fairweather and Usher [9]. If the pumping beam \( L_z \) (see figure 1) is parallel to \( B \), then it is not modulated by the rotating component of \( M \); however, if \( \mathbf{B} \) is an angle between \( \mathbf{B} \) and \( L_z \), then a non-zero projection of the rotating component to \( L_z \) appears, producing a modulation signal. This signal is detected by the quadrature phase detectors and their outputs are fed into additional magnetic coils, nullifying transverse field variations.

A significant modification of this scheme has been proposed [10]. It does not use any additional magnetic fields and, hence, is capable of absolute measurement of the magnetic field vector components. Instead of the forced return of \( B \) to the system axes, varying the direction of the pumping laser beam so that it would follow the direction of \( B \) has been suggested. This scheme is an absolute magnetometer plus perfect laser compass. It means that it is possible to relate the measurement to the earth’s coordinate system simply by measuring the pumping laser beam direction, which can be performed with very high precision. The expected angular accuracy of such a laser compass is extremely high. When converted to the intensity of transverse field components, it is no more than one or two orders of magnitude lower than the resolution of Mx-POPM. This scheme has been modeled numerically [10]. It was shown that it ensures the simultaneous measurement of the modulus of the earth’s magnetic field vector with an absolute accuracy of 0.02 nT and of two angles of deviation of this vector with an absolute accuracy and sensitivity of not worse than 0.4° (0.1 nT) at a measurement time of \( \tau = 1 \) s.

The vector magnetometer based on this scheme does not require recalculation of its readings from the local coordinate system to the world coordinate system, and its accuracy does not depend on the precision of its positioning in space. Its additional advantage is the absence of generated magnetic fields, which enables its use in magnetometric observatories jointly with other devices.

Thus, new methods using CQOPMs allow us to solve various classes of magnetometric tasks, including the simultaneous measurement of the magnetic field modulus and components, and the optical indication of the direction of the magnetic field.

Figure 1. Components of a magnetic moment \( \mathbf{M} \), rotating around magnetic field vector \( \mathbf{B} \parallel \mathbf{z} \). \( L_Z \) is the pumping beam in both Mx and Mz schemes and the detecting beam in Mz scheme; \( L_x \) is the detecting beam in Mx scheme.
References

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