Optics and Spectroscopy, Vol. 78, No. 2, 1995, pp. 292 - 298. Translated from Optika i Spektroskopiya, Vol. 78, No. 2, 1995, pp. 325 - 332.

LASERS AND APPLICATIONS

Laser Pumping in the Scheme of an Mx-Magnetometer

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Received July 28, 1994

Abstract – This paper is devoted to the development of monochromatic radiation sources based on injection lasers intended for optical pumping of alkali metal vapors used in quantum magnetometry. The construction of a single-mode injection laser with an external resonator stabilized by the resonance of saturated absorption in the D_1-line of the K atom is described. The results of investigating fluctuation characteristics of a stabilized laser with an external resonator and the efficiency of laser pumping of ^{39}K vapors are reported. The results obtained demonstrate the high efficiency of laser pumping in comparison with conventional methods. Laser pumping made it possible to obtain the record value of sensitivity of a magnetometric sensor (1.8×10^{-15} T Hz$^{-1/2}$). In the range of intensities necessary for optical pumping of ^{39}K, it is shown that amplitude fluctuations of laser radiation can be reduced to the shot noise.

INTRODUCTION

The development of monochromatic radiation sources on the basis of injection lasers stabilized by narrow reference atomic lines [1 - 3] is of considerable interest for problems of optical pumping of alkali metal vapors [4 - 8]. These radiation sources should find application in quantum magnetometry and in the field of frequency stabilization, where they will be able to replace gas-discharge lamps (Bell–Blum lamps) presently used. It is natural to expect that laser radiation sources, which greatly surpass gas-discharge lamps in radiation monochromaticity and spectral brightness, will make it possible to increase the pumping efficiency in present-day schemes and develop new schemes of optical pumping. As an example, we refer to the scheme of the magnetometer using a hyperfine structure (HFS) of potassium atoms [9]. Employment of a laser in this scheme will considerably increase the pumping efficiency of HFS levels separated by a frequency interval as small as 460 MHz.

The employment of diode lasers for optical pumping imposes certain requirements on their radiation characteristics. Because the factor imposing the principal limitation on the sensitivity of schemes with optical pumping and resonance detection is the noise of the probing light (in most schemes, this light is simultaneously used for optical pumping), amplitude fluctuations of laser radiation must not exceed the shot noise of light of this intensity. Note that gas-discharge lamps, as a rule, satisfy this requirement.

Moreover, the laser wavelength must be locked to the absorption line of the substance being pumped. Requirements for locking accuracy depend on the problem under investigation. They are determined by the need to (1) maximize the overlap integral for the radiation spectrum and the absorption line, which provides the maximum laser pumping efficiency; and (2) minimize optical Stark shifts of the transition being measured, which are induced by pump radiation.

It is not feasible to solve these two problems using conventional pump sources (gas-discharge lamps) for two major reasons. First, the width of their radiation spectrum, as a rule, is considerably greater than the Doppler profile of an absorption line (moreover, it consists of a number of lines and some of them have a destructive effect on pumping). Second, the shape of this spectrum is an uncontrollable function of discharge parameters. However, optical pumping by a laser stabilized by an atomic absorption line makes it possible to satisfy both requirements. Laser stabilization can be performed by both the center of a Doppler absorption line of an atom and resonances of saturated absorption. The latter method seems to be more advantageous because resonances of saturated absorption may be two orders of magnitude narrower than a Doppler line and have practically the same contrast (signal-to-noise ratio).

Here, we describe the construction of a single-mode diode laser with an external resonator, which is stabilized by the resonance of saturated absorption in the D_1-line of the K atom; report investigations of fluctuation characteristics of radiation of the stabilized laser with an external resonator; and present experimental data obtained on the efficiency of laser pumping of ^{39}K vapors.

INJECTION LASER WITH EXTERNAL RESONATOR

The construction of the semiconductor laser with an external resonator (Fig. 1) was developed using the design of the Lebedev Physics Institute, Russian Academy of Sciences, as the basis. The design provided generation of laser radiation a the required parameters: fre-

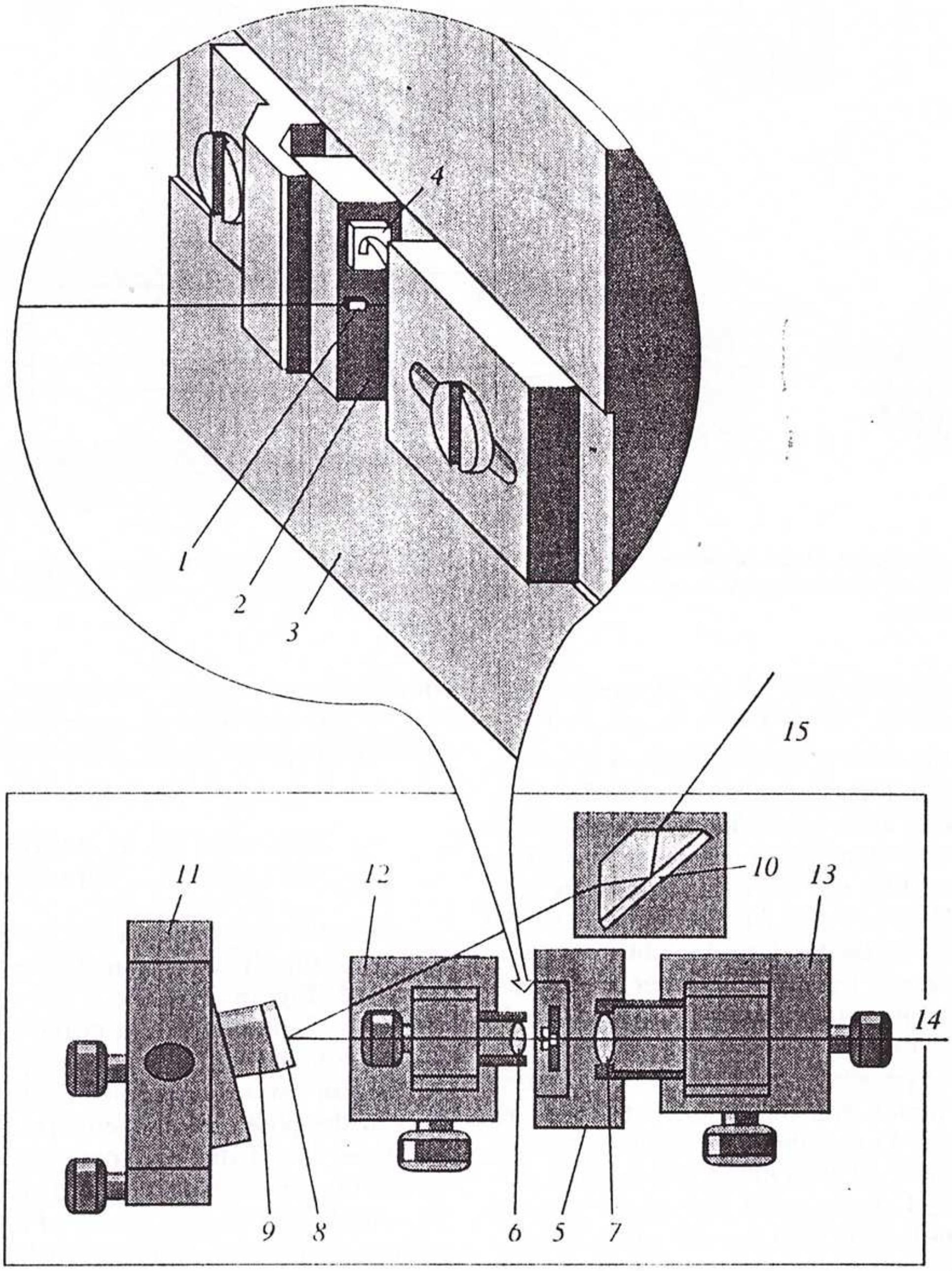

Fig. 1. Laser with external resonator. (*1*) Laser diode, (*2*) copper substrate, (*3*) radiator, (*4*) contact stage, (*5*) cooler, (*6, 7*) focusing lenses, (*8*) mirror with antireflection coating, (*9*) piezoelectric drive, (*10*) diffraction grating, (*11*) mirror mount, (*12, 13*) objective mounts, (*14, 15*) output beams.

quency stability within a range of ±5 MHz; feasibility of locking to an absorption line and tuning within its profile; single-mode lasing with an output power not less than 1 mW; and intensity noise (amplitude noise) comparable to the noise level of a conventional light source (shot noise).

The laser diode represented a Ga–As heterostructure with a laser channel 400 × 5 × 1 μm in size. The rear facet of the chip had a reflecting coating and was used as one of the resonator mirrors. The output facet had an antireflection coating. The laser resonator was formed by the rear facet, a mirror *8*, and a holographic diffraction grating *10* operating in the autocollimation configuration. The grating was cemented to a glass prism rigidly fixed to a slab used as a laser base. Resonator tuning was accomplished by rotating and displacing mirror *8*. Wide-range frequency scanning (up to 30 nm) was performed by an alignment screw rotating the mirror and varying the angle of beam incidence on the grating. Frequency tuning within the instrumental function of the grating was performed by a piezoelectric drive *9*.

The slab forming the laser base was made of devitrified glass, such as Pyroceram, having a zero thermal expansion coefficient. The laser diode temperature was measured by a thermal resistor and controlled by coolers *5*.

The laser electronic unit contains a temperature control circuit, a circuit performing frequency locking and

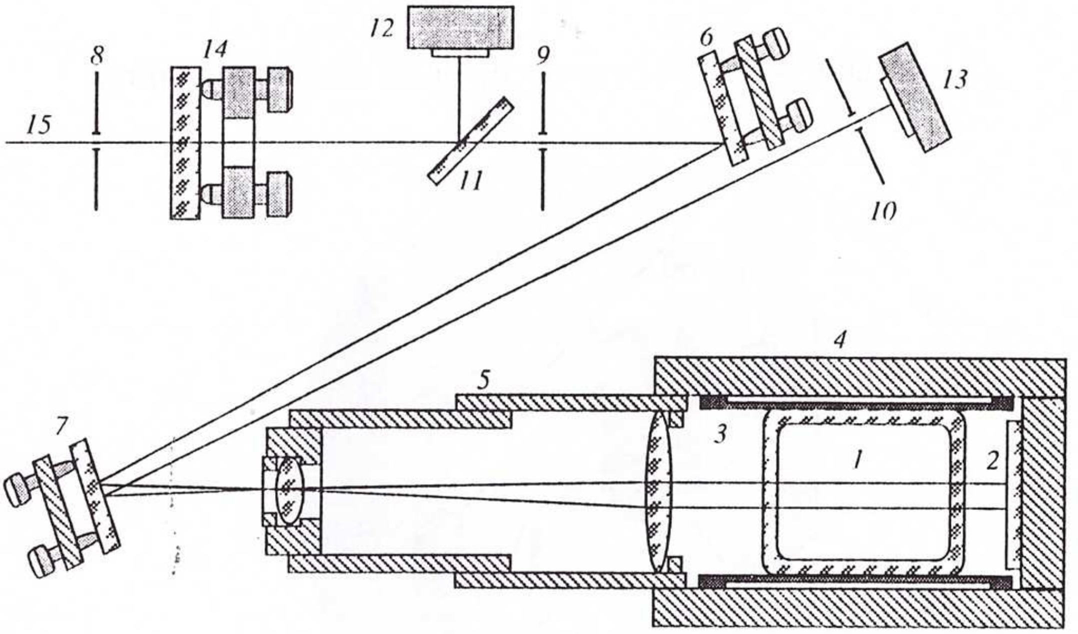

Fig. 2. Optical scheme of the laser diode stabilization. (*1*) Cell with K vapors, (*2*) mirror, (*3*) heater, (*4*) thermostat, (*5*) expanding telescope, (*6*, *7*) mirrors on adjustable mounts, (*8* - *10*) diaphragms, (*11*) beamsplitter, (*12*, *13*) photodiodes, (*14*) interference filter, (*15*) output laser beam.

stabilization, and a highly stable low-noise power supply of the laser diode ($i_{\text{out}} = 0 - 200$ mA, $\Delta i_{\text{out}}/i_{\text{out}} = 10^{-6}$).

Figure 2 illustrates the optical scheme of the diode laser stabilization. In fact, it represents a simple spectrometer of saturated absorption. The scheme consists of the following basic elements: a cell *1* with K vapors; a telescope *5* expanding the laser beam; mirrors *2*, *6*, and *7*; and photodiodes *12* and *13*. The cell *1* is placed in a thermostat *4* with a heater *3* used to obtain the necessary vapor pressure in the cell. The laser beam passing through the cell in two directions provided conditions for observing the double resonance of saturated absorption. A beam passing in one direction was used as the saturating signal, and the other as the probing signal. The telescope *5* expanded the beam diameter by approximately a factor of 10. On the one hand, it provided a proportional decrease of the angle between counterpropagating beams, and, on the other hand, it increased the atom-light interaction time. Thus, the telescope made it possible to decrease flight-path broadening and geometrical broadening and eliminate broadening induced by an optical beam power.

The photodiode *13* was used to observe resonances of saturated absorption. The difference between the two output signals from photodiodes *13* and *12* gave a signal without traces of the tuning laser characteristic.

The spectrum of saturated absorption of ^{39}K contains a number of narrow resonances [10, 13], and the position of the resonance having the highest contrast is practically coincident with the Doppler profile center. This resonance was used for laser frequency stabilization. The error signal formed in the system as a result of frequency modulation of laser radiation (frequency modulation of 15 kHz and frequency deviation from 1 to 5 MHz) was detected, amplified, and used for controlling the piezoelectric drive *9* (Fig. 1).

THE SPECTRAL DISTRIBUTION OF LASER RADIATION NOISE

As noted above, the laser electronic unit contains a dc power supply with intensity fluctuations not exceeding 10^{-6}. Figure 3, curve *a* illustrates a spectrum of intensity fluctuations of laser radiation measured in the range from 1 to 500 kHz. The spectrum of amplitude fluctuations was investigated using synchronous detection of the photodetector electric signal. A fraction of the laser beam directed onto the photodetector produced the photocurrent $I_{\text{ph}} = 20$ μA. The synchronous detector had a frequency band of 0.15 Hz ($\tau = 1$ s). Frequency scanning was accomplished by tuning a reference oscillator. The noise amplitude is given with respect to the shot noise of an ideal light source with the same intensity and is expressed in decibels.

For the given light intensity, as follows from Fig. 3, the measured noise exceeded the shot noise by 20 - 40 dB. It is worth noting that the indication of optical intensity is of primary importance. This is due to the fact that the amplitude of excess noise is proportional to the intensity of light incident on a photodetector, whereas the shot noise amplitude is proportional to the square root of optical intensity. Therefore, the intensity dependence of the ratio of laser and shot noise, which is presented in Fig. 4, varies as the square root of optical intensity (the ratio changes by 10 dB for intensity changes by a factor of 10).

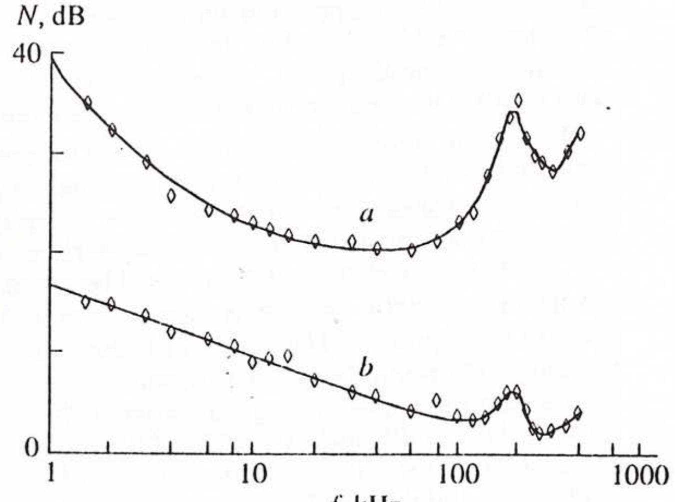

Fig. 3. Spectral distribution of radiation intensity fluctuations of the diode laser (*a*) with a transistor stabilized dc power supply, (*b*) with passive stabilization of the dc power supply.

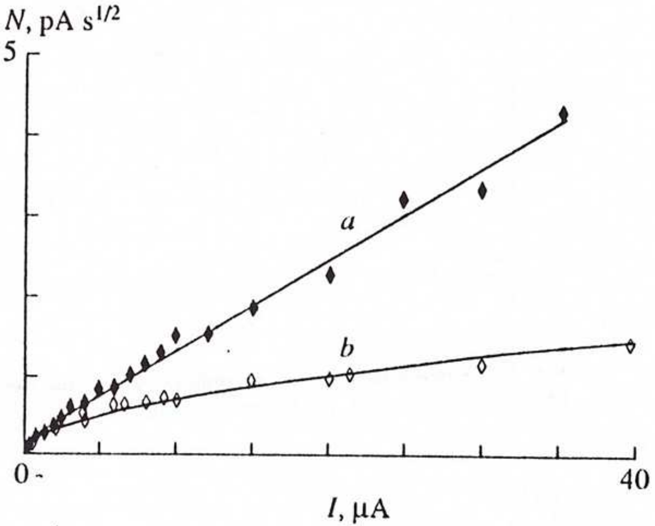

Fig. 4. Dependence of the mean-square amplitude of radiation intensity noise *N* on the light intensity *I*. (*a*) Laser, (*b*) lamp.

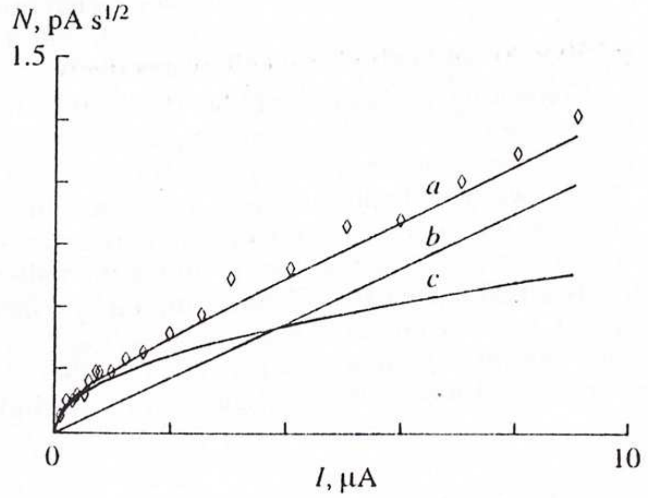

Fig. 5. Dependence of the amplitude of laser intensity noise *N* on the light intensity *I*. (*a*) Total laser noise, (*b*) excess noise, (*c*) shot noise.

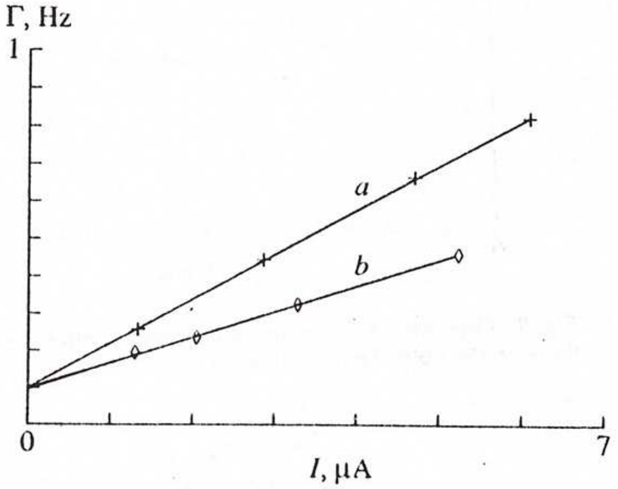

Fig. 6. Dependence of the resonance width Γ on the light intensity *I* (large cell). (*a*) Laser, (*b*) lamp.

To eliminate excess fluctuations of laser radiation, we employed passive stabilization of the laser dc power supply using an RC filter. Figure 4, curve *b* illustrates the results obtained in the case of passive filtration of the current supply. One can see that passive filtration provided a nearly total elimination of excess fluctuations of laser radiation. In the range of hundreds of kilohertz, they were reduced to the level of 2 - 5 dB with respect to the shot noise. The peak of the fluctuation intensity distribution at a frequency of 180 kHz, which was observed prior to filtration, was also eliminated. Therefore, it was of electrotechnical origin.

DEPENDENCE OF NOISE ON THE RADIATION INTENSITY

In the general case, laser radiation noise is a superposition of two noncorrelated processes: excess and shot fluctuations. Investigation of noise as a function of light intensity makes it possible to determine the range in which a laser can be used as a radiation source. Moreover, it allows one to formulate the requirements imposed upon a power supply as a main source of excess noise.

Figures 4 and 5 illustrate dependences of the laser noise amplitude on the light intensity. For comparison, Fig. 4, curve *b* presents the noise amplitude of a gas-discharge lamp (diamonds in Fig. 4, curve *b*) and the theoretical dependence of the shot noise amplitude (in the 0.15-Hz band, $\tau = 1$ s) on the light intensity (solid line in Fig. 4, curve *b*). Figure 5 illustrates the resolution of the laser amplitude noise (curve *a*) into excess (curve *b*) and shot (curve *c*) components. In the intensity range below 4 μA, one can see from the figure that the excess noise of laser radiation in the 0.15-Hz band is about 1.1×10^{-7}, and its contribution to the total noise of laser radiation does not exceed 40%.

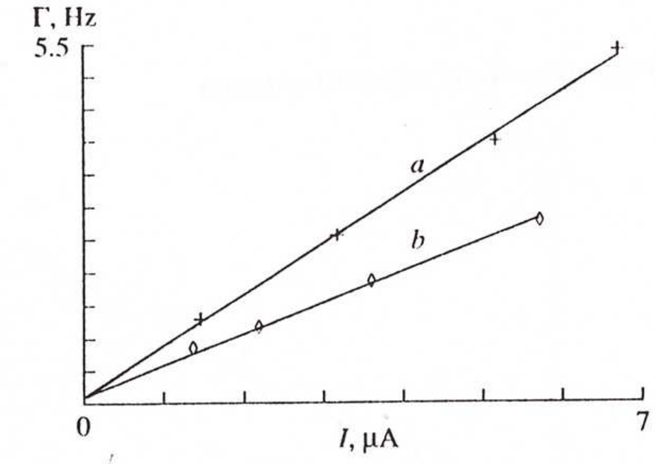

Fig. 7. Dependence of the resonance width on the light intensity (small cell). (*a*) Laser, (*b*) lamp.

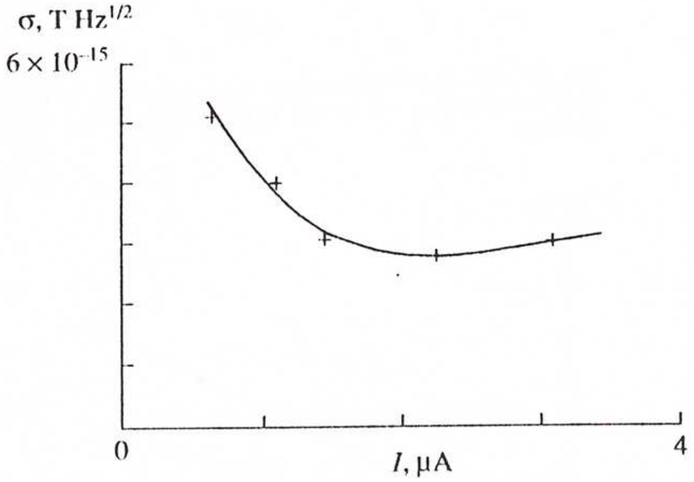

Fig. 8. Dependence of the mean-average variational sensitivity on the optical pump intensity.

LASER PUMPING OF ^{39}K ATOMS

We carried out a series of experiments to investigate the efficiency of laser pumping in the scheme of the Mx-magnetometer operating on a narrow isolated line of potassium [11, 12]. Realization of a narrow line requires limiting the pump intensity and correlates well with conditions for eliminating excess laser noise.

Investigations were performed in a stabilized magnetic field of 0.5 Oe using a conventional single-ray Mx-scheme for observing the double radio-optical resonance in a Zeeman structure of the hyperfine sublevel $F = 2$ of the ground state of K atoms. The frequency of a varying magnetic field was slowly scanned in the vicinity of resonance. The signal of radio-optical modulation of the pump beam that passed through the cell with potassium vapors was synchronously detected. We measured the width and amplitude of the resonance line and compared the latter with the noise level. Light was fed to the cell through a long optical waveguide, allowing a rapid change from lamp to laser excitation.

Under these conditions, we were able to correctly compare the efficiency of laser pumping with the pumping efficiency of a reference lamp.

Figures 6 and 7 illustrate resonance signal broadening in a large (∅150 mm) spherical cell and a small (∅50 × 70 mm) cylindrical cell, respectively.

Comparing resonance widths shows that in both cases the efficiency of laser pumping is 1.7 times higher (due to the monochromaticity of laser radiation) than the efficiency of lamp pumping. Therefore, the pump intensity required to obtain optimum resonance line broadening in the case of laser pumping is smaller than that required in the case of lamp pumping by a factor of $k_p = 1.7$. As a consequence, the amplitude of shot noise for laser pumping is 1.3 times smaller. Moreover, it was found that the efficiency of laser light for

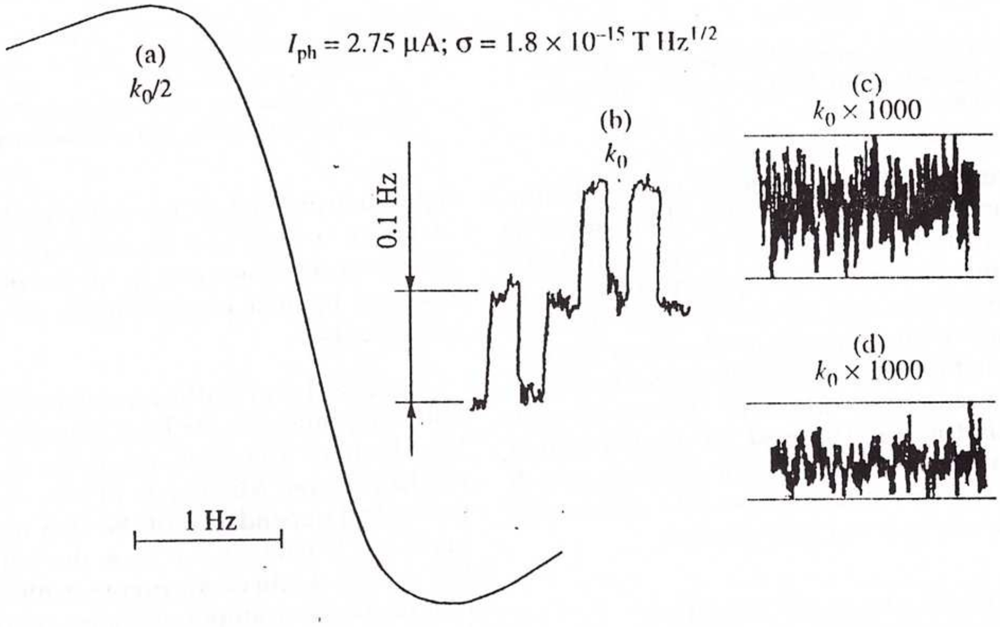

Fig. 9. Variational sensitivity for laser pumping.

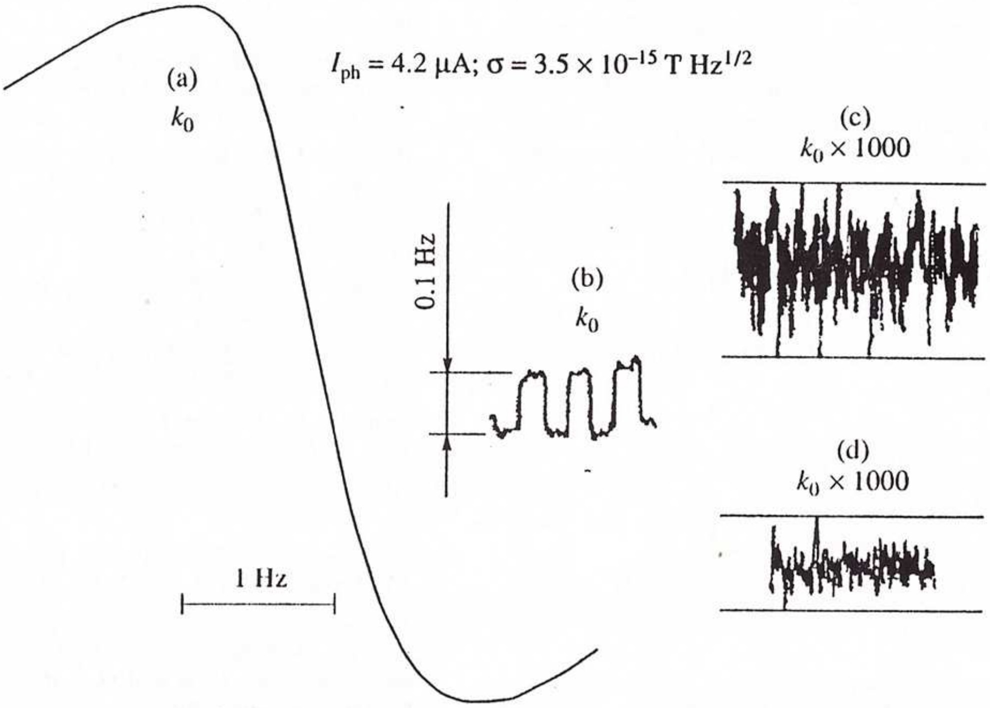

Fig. 10. Variational sensitivity for lamp pumping.

signal detection was higher than that of lamp light by a factor of $k_d = 1.8$. Thus, the quality factor of laser pumping is higher by a factor of $k = k_p k_d = 2.3$.

Figure 8 illustrates the experimental dependence of the mean-square variational sensitivity on the optical pump intensity. The measurements performed at a cell temperature of $T_c = 30°C$ were characterized by a negligible contribution of spin-exchange broadening to the total resonance width. The variational sensitivity was determined from the mean-square noise measured for 100 s. The curve of variational sensitivity has an extremum in the vicinity of the point ≈2.5 μA, corresponding to about a threefold increase of the resonance width. The magnitude of variational sensitivity reaches 2.7×10^{-15} T Hz$^{1/2}$. In the same experimental conditions, the sensitivity of the magnetometer pumped by lamp radiation is equal to 6.0×10^{-15} T Hz$^{1/2}$. Figures 9 and 10 illustrate the limiting sensitivity of the potassium magnetometer. They show (a) recordings of Mx-resonances (k_0 is the gain of the system); (b) change of the signal corresponding to frequency detuning of the radio-frequency field by 0.1 Hz; (c) recordings of photocurrent noise ($k = k_0 \times 1000$) for $\tau = 0.1$ s ($\Delta f = 15$ Hz); and (d) recordings of dark-current photodetector noise ($k = k_0 \times 1000$).

The data presented in Figs. 9 and 10 were obtained at the cell temperature $T_c = 42°C$. This temperature is close to the optimum value for the given experiment configuration. The data in Figs. 9 and 10 correspond to sensitivities of 1.8×10^{-15} T Hz$^{1/2}$ (laser pumping) and 3.5×10^{-15} T Hz$^{1/2}$ (lamp pumping). They support the high efficiency of laser pumping.

CONCLUSION

The results obtained show that laser pumping has a high efficiency in comparison with conventional pumping methods. The employment of laser pumping made it possible to obtain a record value of sensitivity of a magnetometric sensor (1.8×10^{-15} T Hz$^{1/2}$). In the range of intensities needed for optical pumping of ^{39}K, it is shown that amplitude fluctuations of laser radiation can be reduced to shot fluctuations.

One should note the special features of laser pumping and the prospects for its application.

(1) Laser pumping allows (a) maximization of the overlap integral for the radiation spectrum and the absorption line and (b) minimization of optical Stark shifts induced by pump radiation.

(2) The employment of laser pump sources makes it possible to transmit pump radiation to a sensor over extremely long distances through single-fiber optical waveguides, which provides virtually complete absence of magnetic disturbances.

(3) One optical source can be used for pumping several sensors separated in space.

(4) Lasers make it possible to realize new, promising pump schemes such as (a) pumping by modulated light (beat resonance), which allows one to eliminate the radio-frequency field, one of essential sources of systematic errors of a magnetometer; and (b) the magnetometer scheme operating on a hyperfine structure of ^{39}K atoms (the sensitivity of this laser SHF magnetometer greatly exceeds the sensitivity of an SHF magnetometer with lamp pumping).

Note in conclusion that present-day laser applications are restricted by a number of technical factors. First, the system consisting of a laser and a stabilization scheme has large dimensions and power consumption compared to a lamp. Second, this system has a considerably lower immunity to vibrations and acoustic effects. Finally, the laser pumping unit is too expensive in comparison with the lamp pumping unit. However, rapid progress in diode laser engineering gives reason to believe that these restrictions will be eliminated before long.

ACKNOWLEDGMENTS

The authors are grateful to Dr. A.W. Green of the National Geological Survey (USA) for interest in the work and support.

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