Excitation of flexural vibrations of Bloch lines in an oscillating domain wall

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Specific $1D$ magnons localized on Bloch lines have been studied through direct observation of individual Bloch lines in an oscillating domain wall and through photometry of various parts of polarized-light images of these lines. The dispersion law for these magnons has been determined. The frequencies of the resonant vibrations of a Bloch line have been studied as a function of the amplitude of the sinusoidal field used to excite the oscillations of the domain wall. Information on the distribution of spins along the core of a line which is realized at various vibration frequencies has been found through a phase analysis of the motion of sections of the line. The spin flip which occurs in certain parts of a line upon a change in the type of standing wave results from a movement of Bloch points which either exist in the line in its initial state or arise under dynamic conditions.

A nonuniform distribution of spins along a domain wall in a ferromagnet, stemming from a breakup of the domain into subdomains, was observed back in 1952 by Williams and Goertz with the help of a magnetic suspension.[1] Shtrikman and Treves[2] subsequently proposed a structural model for a domain wall containing Bloch lines. However, the recent surge of research interest in this area was triggered by a series of studies of uniaxial garnet films, which revealed that Bloch lines would have to be taken into consideration in order to describe the unusual behavior of magnetic bubbles (cylindrical magnetic domains) in a magnetic field.[3] At present, theoretical and experimental studies of Bloch lines are being carried out on a broad front, but many fundamental questions remain unresolved. In particular, there has been essentially no study of the spectrum of spin waves localized on a Bloch line.

The first experimental study[4] of flexural vibrations of a Bloch line revealed standing flexural waves on the line. A study of these waves made it possible to determine the dispersion law for the corresponding long spin waves. Flexural vibrations of a line proved to be unusual in that there are Bloch points at the nodes of the standing waves, while at antinodes the motion is in accordance with the laws governing the motion of a magnetic vortex. Vibrations of a Bloch line were excited in an yttrium iron garnet single crystal by a sinusoidal external magnetic field, which displaced the line directly along the domain wall. It was thus of interest, in a development of this research, to study the dispersion of flexural vibrations induced in a line by the effect of gyrotropic forces on the line during the oscillation of a domain wall. The primary goal here was to determine the laws governing the dynamic conversion of the line structure which occurs during the formation of various flexural vibration modes of the line. We are reporting the results of a corresponding study in the present paper.

EXPERIMENTAL PROCEDURE

We studied an yttrium iron garnet single-crystal wafer with dimensions of $0.8\times0.35\times0.025$ mm. The domains in this wafer were magnetized in a direction parallel to the (112) plane of the sample and were separated by 180° domain walls. These walls contained Bloch lines, which were tilted slightly toward the surface of the sample. In a transmitting polarizing microscope, each such line was projected onto the plane of the wafer as a dark band separating bright subdomains in a domain wall, distinguished with the help of the Faraday effect.[4] It thus became possible to directly observe changes in the shape of a Bloch line driven by gyrotropic forces, to carry out a photometric study of various sections of the line under these conditions, and to work from the results to study the spectrum of flexural vibrations of the line. This spectrum was studied with a sinusoidal magnetic field H_x applied to the crystal in the direction parallel to the magnetization in the domains. This field caused oscillations of the domain wall. A gyrotropic force proportional to the velocity of the wall acted on the Bloch line.[5]

An SK4-59 spectrum analyzer was used to measure the changes caused in the magnetooptic signal by the motion of the Bloch line. A "MODEL 5202" tuned amplifier was used for a phase analysis of the signal. The magnetic field was produced by Helmholtz coils 6 mm in radius.

EXPERIMENTAL RESULTS

Figure 1 shows some recordings of the magnetooptic signal, which is proportional to the displacement of the entire Bloch line, or of parts thereof, along the oscillating domain wall. The independent variable here is the frequency of the sinusoidal magnetic field H_x. The lower curve was obtained through a photometric study of half the image of a Bloch line. There are several maxima on this curve, the largest corresponding to a frequency $\nu_1 = 1.2$ MHz. When the measurements were repeated under the same conditions, this maximum was always present; the other peaks, in contrast, might shrink or even completely disappear. However, when the intensity of a light beam passed through the central part of the Bloch line was measured, the peak at $\nu_2 = 1.7$ MHz would grow significantly (curve 2), and the first peak might disappear completely. Curve 3 in Fig. 1 demonstrates the possibility of selecting a section of the line for photometric study, in the course of which the $J(\nu)$ at $\nu_3 = 2.5$ MHz increased.

The explanation for this dependence of the peak heights on the position of the region selected for the photometric study is that standing flexural waves of various types are excited at the frequencies ν_n corresponding to these peaks.

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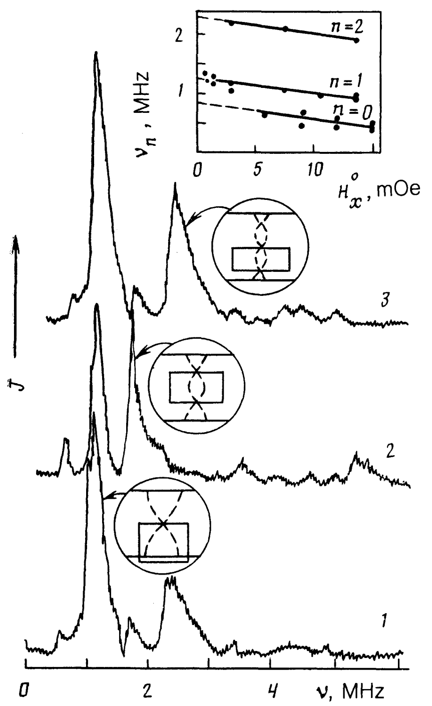

FIG. 1. Magnetooptic signal J, which is proportional to the displacement amplitude of the Bloch line along the domain wall, versus the frequency ν of the magnetic field H_x ($H_x^0 = 15$ mOe). These results were found in a photometric study of various sections of the line, with the Nicol prisms of the microscope slightly uncrossed. The diagram near each curve shows the region (the rectangle) selected for the recording of the photometric curve, along with profiles of the standing waves (dashed lines) which determine the various peaks on the $J(\nu)$ curves. The inset shows the resonant frequencies of the peaks, ν_n, versus the amplitude of the exciting field, H_x.

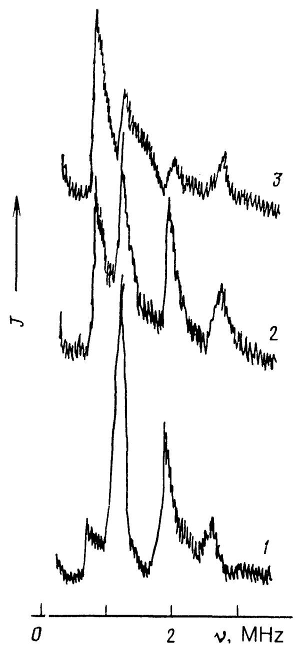

FIG. 2. The magnetooptic signal J versus the frequency ν of the exciting field H_x ($H_x^0 = 7$ mOe) measured at various strengths of the auxiliary static magnetic field H_y, directed perpendicular to the domain wall. 1—$H_y = 0$; 2—1; 3—1.5 Oe.

Their profiles are shown on the diagrams, along with the $J(\nu)$ maxima which they characterize. The regions selected for photometric study are boxed with rectangles. Depending on the vibration frequency, there may be one half-wave ($n = 1$), two half-waves ($n = 2$), or three half-waves ($n = 3$) over the length of the Bloch line. The nodes of the standing wave and their positions on the Bloch line can be observed in the microscope as black points against the background of the diffuse image of the overall line.[4] Since the Bloch line was oscillating out of phase along the domain wall at the neighboring antinodes of the standing wave, according to a study by phase analysis (as discussed below), the magnetooptic signal disappeared when these antinodes overlapped on the path of the measuring light beam. It reached a maximum value during the photometric study of a part of the line between neighboring nodes of the standing wave.

Choosing correspondingly the optimum region for photometric study and studying the image of the oscillating line in a microscope we were also able to distinguish a standing wave corresponding to $n = 4$ ($\nu_4 = 3.0$ MHz). On the curves in Fig. 1, the peak at ν_4 is not seen. There is, however, a small maximum in $J(\nu)$ at $\nu_0 = 0.6$ MHz. The cause of this maximum was determined from the following experimental facts. First, this maximum increased with an increase in the amplitude H_x^0 of the exciting field. Second, a comparison of the curves in Fig. 2 which were measured during the imposition of an auxiliary static field H_y to the crystal, in the direction perpendicular to the domain wall, shows that as H_y is increased the $J(\nu)$ corresponding to ν_0 also increases. The image of the Bloch line oscillating at the frequency of this peak was uniformly blurred, providing evidence of a displacement of the line as a whole.

These results can be explained on the basis that the Bloch line might contain Bloch points in its initial state.[3] If so, the parts of the Bloch line separated by these Bloch points would be acted on by forces in opposite directions, so a uniform motion would be hindered. As the gyrotropic force increases (at higher H_x), on the other hand, the Bloch points might become redistributed or even completely move away from the line, being unfavorable from the energy standpoint at the frequency of a uniform resonance. The points were also moved away from the line by the field H_y magnetizing the line. Further evidence in favor of the latter interpretation comes from the fact that, when the magnetization of the line was reversed by a field H_y in the opposite direction, the phase of the uniform resonant vibrations of the line changed by an amount π under the influence of the gyrotropic force. The peak at the frequency ν_0 was thus determined by a resonance of a uniform displacement of the Bloch line.

The frequencies ν_n corresponding to the maxima on the $J(\nu)$ curve depend on the amplitude of the alternating field H_x applied to the crystal. These curves could be measured for only the first three peaks ($n = 0$, 1, and 2) in a small interval of H_x^0 values (see the inset in Fig. 1), since a further increase in H_x^0 resulted in sharp changes in the nature of the $J(\nu)$ curve, apparently because of irreversible structural conversions of the Bloch line (or of the domain wall).

Figure 3a shows hodographs of the magnetooptic signal in the complex plane. These hodographs were recorded with the help of a MODEL 5202 tuned amplifier in the frequency region in which the flexural vibrations with $n = 1$ were excit-

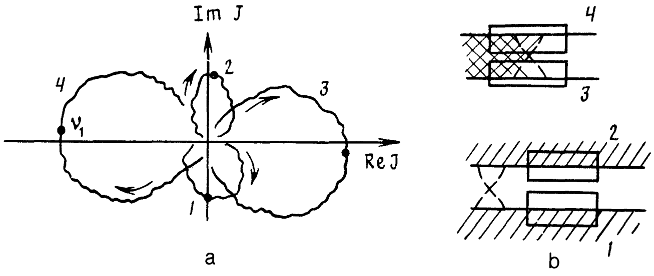

FIG. 3. a: Hodographs of the magnetooptic signal J recorded in the complex plane for frequencies ~ 0.9 to ~ 1.4 MHz of the exciting field H_x during a photometric study of various regions of the domain wall near a Bloch line. The frequency ν_1 on the hodographs is shown by the points. Here $H_x^0 = 15$ mOe. b: Profiles of the standing wave on the Bloch line (dashed lines) and regions (rectangles) selected for photometric study during the recording of hodographs 1–4.

ed (the regions on the hodographs corresponding to ν_1 are marked with points). The beginning of each curve corresponds to $\nu \approx 0.9$ MHz, and the end to $\nu \approx 1.4$ MHz. We see that as the frequency is varied over the specified interval the phase of the oscillations of the signal changes by π, as expected. Figure 3b shows profiles of the standing wave at the maximum line displacement amplitudes (the dashed lines), along with the regions (boxed with rectangles) selected for the photometric study which resulted in these curves. Hodographs 1 and 2 characterize the phase and amplitude of the oscillations of the domain wall (and thus of the Bloch line along the y direction) as a function of the frequency of the exciting field.

Analysis of these curves with allowance for the black-and-white contrast which was realized during their recording (Fig. 3b) shows that the two halves of a wall oscillate in phase. On the other hand, the vibrations of the line along the wall at one antinode of the standing wave lag $\sim \pi/2$ in phase behind the oscillations of the wall (hodograph 3). At the neighboring antinode of the wave, the oscillations of the line were out of phase with the former (hodograph 4). The phase shift of the oscillations of the line along mutually perpendicular directions occurred because the gyrotropic force which displaced the line along the wall was proportional to the velocity of the wall,[5] which lagged $\pi/2$ in phase behind the driving force. The out-of-phase oscillations of the Bloch line along the wall at the neighboring antinodes of the standing wave, during an in-phase oscillation in the perpendicular direction under the action of gyrotropic forces on the wall, can be explained by assuming an opposite polarization of the spins in the core of the Bloch line in neighboring regions of the line. In other words, these results are evidence that there is a Bloch point at the node of the standing wave.

The existence of this point is also indicated by the displacement of the node of the standing wave at a frequency $\nu \neq \nu_1$ caused by the auxiliary field H_y which magnetized the Bloch line.[6] In contrast with the situation in which the flexural vibrations of the Bloch line were excited directly by the external magnetic field,[4] however, in the case at hand we generally did not observe a nucleation of a Bloch point at the end of the Bloch line or its motion along the line upon a variation of the frequency of the field H_x during the formation of a standing wave at the frequency ν_1. These processes were observed only after an intense excitation of a resonant,

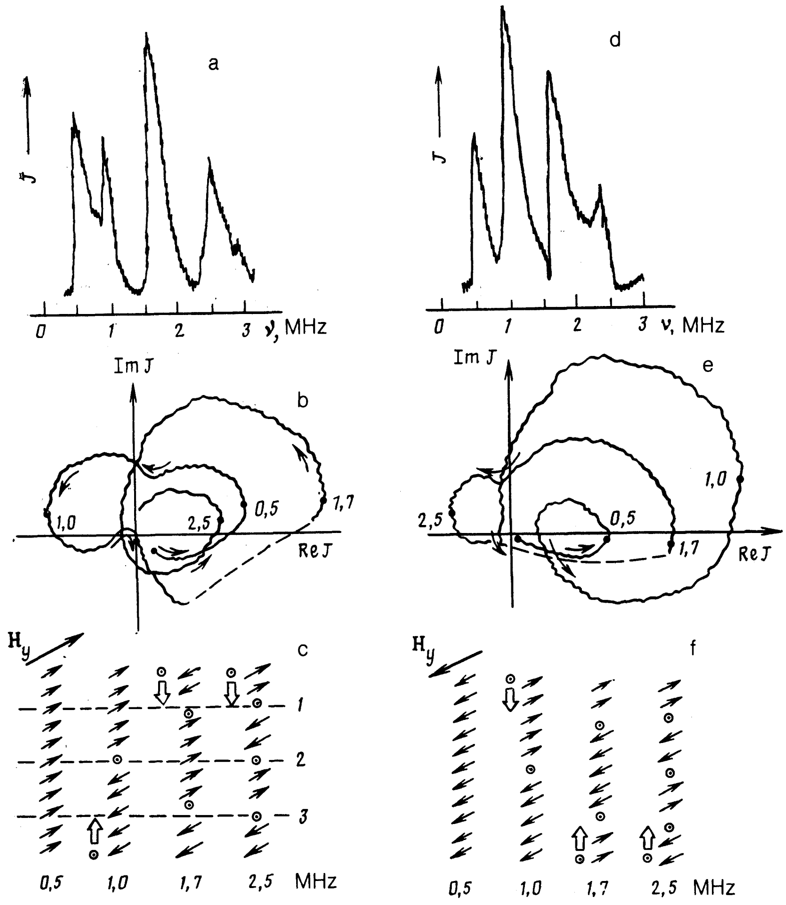

FIG. 4. $J(\nu)$ spectra (a, d) and corresponding hodographs in the complex plane (b, e) recorded in a photometric study of two neighboring regions of a line which were at antinodes of the standing wave at the frequency ν_3, with $H_y = -3$ Oe and $H_x^0 = 15$ mOe. The the resonant frequencies ν_n are given on the hodographs, near the corresponding points. The dashed lines on hodographs b and e correspond to sharp changes in J (a, d). c, f) That distribution of spins along the core of the Bloch line which is realized at resonant frequencies ν_n with (c) $H_y = -3$ Oe and (f) $+3$ Oe. The regions of the Bloch line bounded by the horizontal dashed lines 1 and 2, and by lines 2 and 3, were selected for the recording of the photometric curves shown in Fig. 4, a and b, and Fig. 4, d and e, respectively.

uniform displacement of the Bloch line at the frequency ν_0. In other words, these processes occurred only in a prepolarized Bloch line.

Figure 4 shows some hodographs which we recorded for the magnetooptic signal, which is proportional to the displacement of the Bloch line along the domain wall, over the entire frequency spectrum. To obtain more definite results, we carried out the measurements in an auxiliary field H_y, which polarized the spins in the core of the line in its initial state.

The points on the hodographs show the regions corresponding to the resonant frequencies. The spectrum $J(\nu)$ in Fig. 4a and the corresponding hodograph (Fig. 4b) were recorded during a photometric study of the section of the line between the nodes of the standing wave which was excited at $\nu_3 = 2.5$ MHz. It can be seen from an analysis of the parts of the hodograph corresponding to the resonant peaks on the $J(\nu)$ curve that each time the signal passes through a maximum the phase of its vibrations changes by π. However, while the phase of the vibrations of a local section of the line changes by an amount $\sim\pi$ (as expected) as ν is increased from ν_0 to ν_1, and also from ν_1 to ν_2, the oscillations of the signal at ν_2 and ν_3 are essentially in phase. The reason for the latter result is that during the formation of the vibration mode corresponding to ν_3 the spins in the core of this section of the line were flipped as a result of the passage of a Bloch point through it. As a result, there was an additional change of π in its vibration phase. The spin distribution corresponding to these results in the core of the section of the line selected for the measurements is shown in Fig. 4c for all the resonant frequencies (the region selected for the photometric study is bounded by dashed lines 1 and 2). The circles here show the positions of Bloch points at the nodes of the standing waves. The polarization of the spins in this section of the line remained the same at ν_0 and ν_1, was practically the same at ν_2, and was reversed at ν_3.

The $J(\nu)$ spectrum and the hodograph shown in Fig. 4, d and e, were measured in a photometric study of a neighboring section of the line, corresponding to the section between dashed lines 2 and 3 in Fig. 4c. In this section of the line, as we see from the hodograph, the phase of the oscillations in this signal is essentially the same at ν_0, ν_1, and ν_2, but it changes by π as ν increases from ν_2 to ν_3. This result means that the spins in its core flip during the formation of the standing waves for $n = 1$ and 2, but they do not as the frequency goes from ν_2 to ν_3 (Fig. 4c).

Measurements of this sort at all the antinodes of the standing waves of the oscillating Bloch line made it possible to determine that distribution, realized at the resonant frequencies ν_n, of the spins along the core over the entire length of the line which was (Fig. 4c). These measurements also revealed the directions in which the Bloch points moved (the double arrows in Fig. 4c) during the successive increases in the frequency of the exciting field. The appearance and movement of Bloch points along the Bloch line at frequencies close to ν_1 and ν_2 could be seen directly in the field of view of the microscope. The distribution of the spins along the line, which was realized at the frequency $\nu_3 = 2.5$ MHz, was constructed solely from an analysis of the vibrations of the line along the wall. It was assumed that its vibrations along the y axis at neighboring antinodes of the wave are in phase, as in the case corresponding to Fig. 3.

Figure 4f shows the spin distribution in the core of a Bloch line oscillating at resonant frequencies ν_n. This distribution was determined in the same way as above, but after a reversal of the field H_y. Comparing Figs. 4c and 4f, we see that when H_y is reversed there are changes in the direction in which the Bloch points move as the frequency of the exciting field H_x is raised. Consequently, the regions where these points nucleate change. Curiously, however, while the polarization of the spins in the Bloch line in the even modes of flexural vibrations ($n = 0$ and 2) is inverted when H_y is reversed, for the odd modes ($n = 1$ and 3) this polarity is independent of the polarity of H_y.

The hodographs of the magnetooptic signal, measured on a Bloch line oscillating in the absence of a field H_y, are quite different from those shown above. In the first place, they frequently do not have regions corresponding to a uniform resonance of the line, which is usually not observed at $H_y = 0$. Second, the nature of the curves is evidence that the spins may flip simultaneously in different parts of a line when the mode of the flexural vibrations of the line forms. This result is one more piece of evidence in favor of the suggestion that the "demagnetized" Bloch line contains Bloch points, which are capable of moving (reversing the polarization of sections of the line) and also of annihilating, grouping into clusters, or accumulating at nodes of standing waves, preventing their formation. Evidence for this suggestion comes from the results of many measurements of the spectra $J(\nu)$ and their hodographs in the absence of the field H_y. They frequently had a complex shape, which varied from measurement to measurement.

DISCUSSION OF RESULTS

The primary accomplishment of these experiments was the identification of standing flexural waves which arise on Bloch lines in an oscillating domain wall. It turns out that their resonant frequencies ν_n depend on the wall vibration amplitude. To determine the actual values ν_n^0 of the natural vibrational modes of the line, the values ν_n measured at various of H_x^0 were extrapolated to $H_x^0 = 0$ (see the inset in Fig. 1). The values ν_n^0 obtained in this fashion are shown in Fig. 5 as a function of the index of the peak on the $J(\nu)$ curve (the open circles; the filled circles were obtained in measurements at a common value of H_x^0). Here $n = dk/\pi$, where d is the length of the Bloch line (~ 25 μm), and k is the wave vector. The $\nu_n^0(n)$ curve thus essentially reflects the disper-

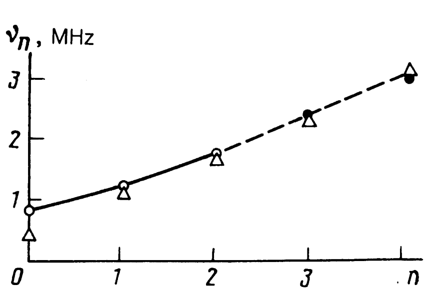

FIG. 5. Resonant frequency ν_n of a peak versus the index n of the peak, as constructed from the experimental data of the present study (○, ●) and the data of Ref. 4 (Δ).

sion $\omega(k)$ of the long, one-dimensional spin waves localized on the Bloch line. It is essentially the same as the dispersion curve (the triangles in Fig. 5) found during excitation of the line by a magnetic field directed perpendicular to the plane of the wafer.[4] Consequently, flexural vibrations of a given type of a Bloch line can be excited by magnetic fields in different orientations. This result is evidence that specific properties of the line—properties of a magnetic vortex—are being manifested in the flexural vibrations.[5]

The observed behavior of the values of ν_n as a function of the amplitude of the exciting field, H_x^0, is similar to $\nu_n(H_x^0)$ for the case of natural flexural vibrational modes of a unipolar domain wall in this type of ferromagnet:[7] As H_x^0 increases, ν_n decreases. Consequently, as in the case described in Ref. 7, this behavior of the Bloch line appears to be determined by a "magnetic aftereffect."

Studies of a Bloch line driven by gyrotropic forces have also made it possible to find fairly convincing evidence on the laws governing the dynamic conversion of the structure of the line and regarding a substantial effect of Bloch points on the dynamics of the line. These points are present in a line not only at the resonant frequencies but also at all intermediate frequencies; they are furthermore in the initial state of the line. The spin distribution in the Bloch line associated with these points depends on the external magnetic fields and the velocity of the wall, redetermining the intensity and nature of the flexural vibrations of the line and thus its contribution to the spectrum of spin waves in the crystal.

CONCLUSION

Summarizing these results for a slightly anisotropic ferrimagnet, we should distinguish two circumstances of fundamental importance.

1. In a domain wall oscillating under the influence of a uniform external magnetic field, natural flexural vibrations of Bloch lines are excited. These vibrations are polarized elliptically and have Bloch points at the nodes of the standing waves.

2. The excitation of lines even at relatively low amplitudes of the wall vibration (amplitudes comparable to the thickness of the wall) is quite strong and may be accompanied by definitely nonlinear processes in which the structure of the lines changes.

[1] H. J. Williams and M. Goertz, J. Appl. Phys. **23**, 316 (1952).
[2] S. Shtrikman and D. Treves, J. Appl. Phys. **31**, 375 (1960); J. Appl. Phys. **31**, 1304 (1960).
[3] A. P. Malozemoff and J. C. Slonczewski, *Magnetic Domain Walls in Bubble Materials*, Academic, Orlando, 1979 (Russ. Transl. Mir, Moscow, 1982, p. 382).
[4] L. M. Dedukh, Yu. P. Kabanov, and V. I. Nikitenko, Zh. Eksp. Teor. Fiz. **97**, 570 (1990) [Sov. Phys. JETP **70**, 317 (1990)].
[5] A. V. Nikiforov and É. B. Sonin, Pis'ma Zh. Eksp. Teor. Fiz. **40**, 325 (1984) [JETP Lett. **40**, 1119 (1984)].
[6] Yu. P. Kabanov, L. M. Dedukh, and V. I. Nikitenko, Pis'ma Zh. Eksp. Teor. Fiz. **49**, 551 (1989) [JETP Lett. **49**, 637 (1989)].
[7] L. M. Dedukh, V. I. Nikitenko, and V. T. Synogach, Zh. Eksp. Teor. Fiz. **94**, 312 (1988) [Sov. Phys. JETP **67**, 1912 (1988)].

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