Surface spin waves in a Heisenberg ferrimagnet with a single-ion anisotropy (uniaxial and nonuniaxial)

Wen-Zhong Shen
Department of Physics, Suzhou University, Suzhou 215006, China
*and National Laboratory for Infrared Physics, Shanghai Institute of Technical Physics, Academia Sinica, Shanghai 200083, China**

Zhen-Ya Li
Chinese Center for Advanced Science and Technology (World Laboratory), P.O. Box 8730, Beijing, 100080, China
*and Department of Physics, Suzhou University, Suzhou 215006, China**

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Surface spin waves on the (001) surface layer of a semi-infinite CsCl-type (bcc) Heisenberg ferrimagnet with a single-ion anisotropy, uniaxial and nonuniaxial, are investigated by use of Green's-function techniques. It is found that the spectrum of the surface spin waves is related to the strength of the anisotropy, and that only the optical branches can exist in the presence of anisotropy on the surface or in the bulk. In the uniaxial anisotropy case, there is a critical value of the surface-anisotropy parameter, below which the optical branches of the surface spin waves cannot be excited. For the nonuniaxial anisotropy case, it is found that surface spin waves cannot be excited in the vicinity of the Brillouin-zone boundary, if the surface anisotropy is weak enough. The effect of surface-exchange interactions on the surface spin-wave spectrum has also been discussed.

I. INTRODUCTION

In recent years, many experiments have shown the existence of anisotropy fields in magnetic systems, and these fields are found to play an important role in determining the magnetic properties of such materials. These experimental investigations give an impetus to theoretical studies on this subject. The effects of single-ion uniaxial anisotropy on the magnetic properties of ferromagnets and antiferromagnets have been extensively studied;[1–4] though the nonuniaxial anisotropy more widely exists in magnetic materials, only the ferromagnet with single-ion nonuniaxial anisotropy has been treated by a few authors.[5–7]

So far as we know, few investigations have been reported on the ferrimagnet with single-ion uniaxial and nonuniaxial anisotropy and, particularly, on the effects of anisotropy on surface magnetism in the ferrimagnet.[8] Experiments have demonstrated the possible existence of a very strong anisotropy field at the surface, so that much attention has been drawn to the effect of surface anisotropy recently.[9–12] The aim of this paper is to investigate the surface spin-wave (SSW) spectrum on the (001) surface of a semi-infinite CsCl-type (bcc) Heisenberg ferrimagnet with a single-ion uniaxial and nonuniaxial anisotropy by use of Green's-function techniques, which are convenient to treat systems that lack full translational symmetry and provide us with information about the surface magnons.

The paper is organized as follows: We first discuss the case of single-ion uniaxial anisotropy in a semi-infinite ferrimagnet in Sec. II. Section III is devoted to the ferrimagnet with single-ion nonuniaxial anisotropy, and some concluding remarks and discussions are presented in Sec. IV.

II. SINGLE-ION UNIAXIAL ANISOTROPY

A. Theory

We consider a semi-infinite CsCl-type (bcc) two-sublattice Heisenberg ferrimagnet with a single-ion uniaxial anisotropy and with the first two atomic layers defined as belonging to sublattices A and B, respectively. The Hamiltonian of the system may be given as

$$\hat{\mathbf{H}} = -\sum_{\langle ij\rangle} J_{ij}\hat{\mathbf{S}}_i\cdot\hat{\mathbf{S}}_j - \sum_i D_i (S_i^z)^2 , \tag{1}$$

where J_{ij} represents the exchange interaction between nearest-neighbor spins, the amplitude of spin S_i is denoted by S_a (or S_b) when site i belongs to sublattice A (or B), and D_i is the single-ion anisotropy parameter, which measures the strength of anisotropy at site i. We take $D_i = D_{as}$ on the surface plane, and otherwise $D_i = D_a$ (or D_b) if site i belongs to sublattice A (or B). The surface is assumed parallel to the (001) plane.

We define a retarded Green's function of the form $\langle\langle \hat{\mathbf{S}}_l^+;\hat{\mathbf{S}}_m^-\rangle\rangle$, denoted as $G_{lm}(\omega)$.[13,14] In terms of the Hamiltonian (1) of the system, the equations of motion may be written as

$$\omega\langle\langle \hat{\mathbf{S}}_l^+;\hat{\mathbf{S}}_m^-\rangle\rangle = \langle[\hat{\mathbf{S}}_l^+,\hat{\mathbf{S}}_m^-]\rangle + \langle\langle[\hat{\mathbf{S}}_l^+,\hat{\mathbf{H}}];\hat{\mathbf{S}}_m^-\rangle\rangle . \tag{2}$$

The explicit form of the Green's function $G_{lm}(\omega)$ is obtained as

$$\left\{\omega - \left[2D_l\langle S_l^z\rangle + \sum_\delta J_{l,l+\delta}\langle S_{l+\delta}^z\rangle\right]\right\}G_{lm}(\omega) + \langle S_l^z\rangle\left[\sum_\delta J_{l,l+\delta}G_{l+\delta,m}(\omega)\right] = 2\langle S_l^z\rangle\delta_{lm} , \tag{3}$$

where $G_{lm}(\omega)$ are the Fourier transform of the Green's functions and we have employed a random-phase-approximation (RPA) decoupling. δ denoted the relative position vector between two nearest neighbors, and $\sum_\delta$ represents the sum over such nearest neighbors.

We now utilize the properties of translational invariance in the planes which are parallel to the surface and introduce the two-dimensional Fourier transformation of the Green's function $G(\mathbf{K}_\parallel, E)$, where the wave vector $\mathbf{K}_\parallel = (K_x, K_y)$ is a two-dimensional wave vector parallel to the surface. It is easy to show that the Green's functions satisfy the matrix equation

$$(\omega - \hat{\underline{\mathbf{F}}})\hat{\underline{\mathbf{G}}} = \hat{\underline{\mathbf{I}}} \ , \tag{4}$$

where $\underline{F}$, $\underline{G}$, and $\underline{I}$ are infinite-dimensional square matrices. $\underline{I}$ denotes a unit matrix, and $\underline{F}$ is given by

$$\hat{\underline{\mathbf{F}}} = \begin{bmatrix} F'_a & -K_1 & 0 & 0 & \cdots & & & & & \\ -K_2 & F_b & -K_2 & 0 & \cdots & & & & & \\ 0 & -K_1 & F_a & -K_1 & \cdots & & & & & \\ \vdots & \vdots & \vdots & \vdots & & \vdots & \vdots & & & \\ & & & & & -K_2 & F_b & -K_2 & 0 & \cdots \\ & & & & & 0 & -K_1 & F_a & -K_1 & \cdots \\ & & & & & \vdots & \vdots & \vdots & \vdots & \end{bmatrix} , \tag{5}$$

where

$$\begin{aligned} F'_a &= 2D_{as}M_1 + 4JM_2 \ , \\ K_1 &= \lambda J M_1 \ , \\ F_b &= 2D_b M_2 + 8JM_1 \ , \\ K_2 &= \lambda J M_2 \ , \\ F_a &= 2D_a M_1 + 8JM_2 \ , \\ \lambda &= 4\cos(K_x a_0/2)\cos(K_y a_0/2) \ , \end{aligned} \tag{6}$$

M_1, M_2 stand for the magnetization of sublattices A, B, respectively, and a_0 is the lattice constant of each sublattice.

Introducing the two transfer functions[14,15]

$$\begin{aligned} T_1 &= G_{2l+1,1}/G_{2l,1} \ , \\ T_2 &= G_{2l,1}/G_{2l-1,1} \ , \quad l \geq 1 \end{aligned} \tag{7}$$

and substituting T_1 and T_2 into Eq. (4), we obtain[14]

$$G_{1,1} = (\omega - F'_a + K_1 T_2)^{-1} \ , \tag{8}$$

where

$$T_2 = -\{(\omega - F_a) \pm [(\omega - F_a)^2 - 4K_1K_2(\omega - F_a)/(\omega - F_b)]^{1/2}\}/(2K_1) \ .$$

In a similar manner, we can obtain the Green's functions in the other successive layers. Because each layer Green's function has the same singularity,[14] we can easily find the SSW spectrum equation,

$$\omega - F'_a + K_1 T_2 = 0 \ , \tag{9}$$

and the two solutions are

$$\begin{aligned} \omega_\pm = {} & [F_b + F'_a - K_1K_2/(F_a - F'_a)]/2 \\ & \pm \{(F_b - F'_a)^2 + 2K_1K_2(2F_a - F'_a - F_b)/(F_a - F'_a) \\ & + [K_1K_2/(F_a - F'_a)]^2\}^{1/2}/2 \ . \end{aligned} \tag{10}$$

Thus we can obtain the SSW spectrum of the system from the above equation.

B. Results

We show in Fig. 1 the SSW spectrum for some selected values of anisotropy strength in the cases $S_a > S_b$ and $S_a < S_b$. From Fig. 1 we can easily find that the spectrum of the SSW is very sensitive to the strength of the anisotropy. For simplicity, we have assumed that the anisotropy parameter of the surface is the same as that of the bulk. In the absence of anisotropy both on the surface and in the bulk, only one of the two branches, acoustic and optical, of SSW can be excited in the case $J < 0$. The acoustic branch can be found for $S_a > S_b$, while the optical branch can be found for $S_a < S_b$, as shown by curve a in Fig. 1. In the presence of surface and bulk anisotropy, only the optical branches can be excited. The frequency of the SSW increases with the increase of the strength of the anisotropy. We also give the negative-energy curves of the SSW, but they cannot be excited.[14]

In order to examine the influence of the surface anisotropy D_{as} on the SSW spectrum, we plot in Fig. 2 the dispersion curves of the SSW with different D_{as} (D_a and D_b are assumed to be same) in the case $S_a > S_b$. We find that the frequency of the SSW spectrum increases with the surface anisotropy, and the larger the anisotropy in the bulk, the larger the frequency of the SSW, while in the case $S_a < S_b$ a similar result is also obtained.

As mentioned above, only the optical branch can be excited in the presence of anisotropy on the surface or in the bulk. But when the surface anisotropy D_{as} becomes negative, we can see from Fig. 3 that for strong surface anisotropy neither the acoustic nor the optical branch can be excited, while for weak surface anisotropy there is one optical branch that can be excited as before. Therefore there is a critical value D_{as}^{c} of the surface-anisotropy parameter, below which even the optical branch of the SSW will not be excited. In the case $S_a > S_b$, we have taken $M_1=1.5$, $M_2=-1.0$, $J=-1.0$ and have obtained

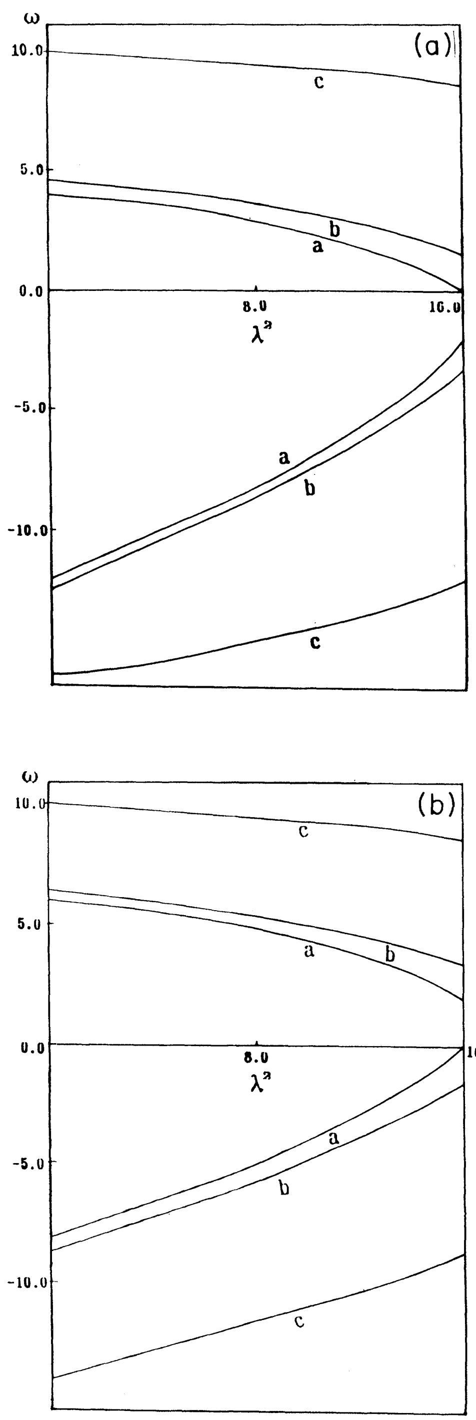

FIG. 1. Dispersion curves of the SSW with $D_{as}=D_a,D_b$: (a) $S_a > S_b$, $M_1=1.5$, $M_2=-1.0$, and $J=-1.0$; (b) $S_a < S_b$, $M_1=1.0$, $M_2=-1.5$, and $J=-1.0$. The different curves correspond to $D_{as}=D_a=D_b=0.0$ (curve *a*), $D_{as}=D_a=D_b=0.2$ (curve *b*), and $D_{as}=D_a=D_b=2.0$ (curve *c*).

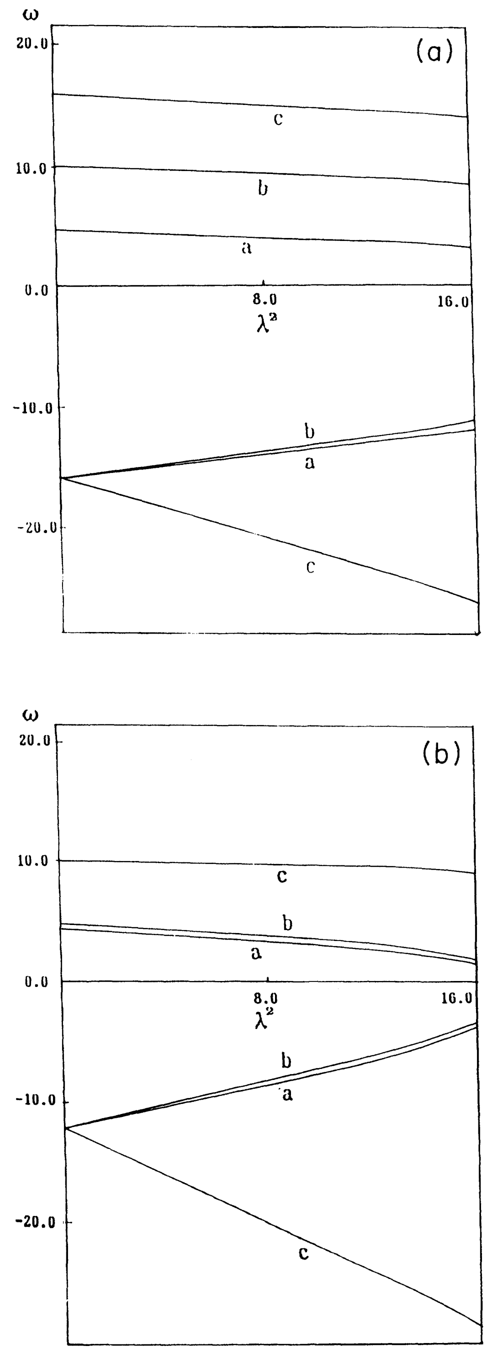

FIG. 2. Dispersion curves of the SSW with different D_{as} (D_a and D_b are assumed to be same) in the case of $S_a > S_b$, $M_1=1.5$, $M_2=-1.0$, and $J=-1.0$: (a) $D_a=D_b=2.0$. The different curves correspond to $D_{as}=0.2$ (curve *a*), $D_{as}=2.0$ (curve *b*), and $D_{as}=4.0$ (curve *c*). (b) $D_a=D_b=0.2$. The different curves correspond to $D_{as}=0.1$. (curve *a*), $D_{as}=0.2$ (curve *b*), and $D_{as}=2.0$ (curve *c*).

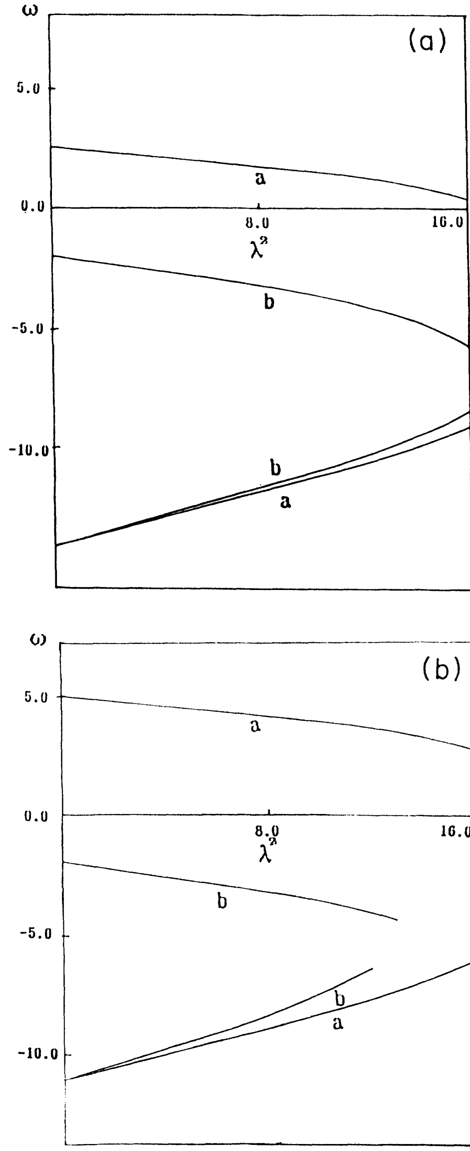

FIG. 3. SSW spectrum with $D_{as}<0$: (a) $S_a>S_b$ with $M_1=1.5$, $M_2=-1.0$, and $J=-1.0$. $D_{as}=-0.2$ and $D_a=D_b=1.0$ (curve *a*); $D_{as}=-2.0$ and $D_a=D_b=1.0$ (curve *b*). (b) $S_a<S_b$ with $M_1=1.0$, $M_2=-1.5$, and $J=-1.0$. $D_{as}=-0.5$ and $D_a=D_b=1.0$ (curve *a*); $D_{as}=-4.0$ and $D_a=D_b=1.0$ (curve *b*).

$D_{as}^c=-1.33$ for the surface-anisotropy parameter. It is found that the critical value D_{as}^c is independent of the bulk-anisotropy strength, but it is dominated by interaction between spins on the surface as well as spins of the surface with that of the nearest layer in the bulk, and is dependent on S_a and S_b. In the case $S_a<S_b$, the critical value D_{as}^c of the surface anisotropy is -3.0, which is different from that of the case $S_a>S_b$. Further, we have, approximately, $D_{as}^c=-2S_b/JS_a$.

III. SINGLE-ION NONUNIAXIAL ANISOTROPY

A. Theory

We here still consider a semi-infinite CsCl-type (bcc) two-sublattice Heisenberg ferrimagnet consisting of layers of a square lattice with a (001) surface. The Hamiltonian of the system with single-ion nonuniaxial anisotropy may be written as[5-7,14]

$$\hat{\mathbf{H}}=\frac{1}{2}\sum_{\langle ij\rangle}J_{ij}\hat{\mathbf{S}}_i\cdot\hat{\mathbf{S}}_j-\sum_i D_i(S_i^z)^2-\sum_i F_i[(S_i^x)^2-(S_i^y)^2]$$

$$-\sum_j D_j'(S_j^z)^2-\sum_j F_j'[(S_j^x)^2-(S_j^y)^2]\ , \qquad (11)$$

where J_{ij} is the exchange interaction between two nearest-neighbor spins and D_i (D_j') and F_i (F_j') are anisotropy parameters at site i (j) for the uniaxial and nonuniaxial terms, respectively. We also assume that the first two atomic layers belong to sublattices A and B, respectively, the subscript i (j) represents the site of sublattice A (B), and the amplitude of spin S_i (S_j) is denoted as S_a (S_b).

We restrict ourselves to the low-temperature region of $T\ll T_c$. By use of the Holstein-Primakoff transform and the linear spin-wave approximation, retaining terms up to the second order in the boson operators $a_i^\dagger$, a_i, $b_j^\dagger$, and b_j, we have

$$\hat{\mathbf{H}}=\sum_i\left[2D_iS_a\eta+\sum_j J_{ij}S_b\right]a_i^\dagger a_i+\sum_j\left[2D_j'S_b\eta'+\sum_i J_{ij}S_a\right]b_j^\dagger b_j$$
$$+\sqrt{S_aS_b}\sum_{\langle ij\rangle}J_{ij}(a_ib_j+a_i^\dagger b_j^\dagger)-S_a\eta^{1/2}\sum_i F_i(a_i^\dagger a_i^\dagger+a_ia_i)-S_b\eta'^{1/2}\sum_j F_j'(b_j^\dagger b_j^\dagger+b_jb_j)\ , \qquad (12)$$

where

$$\eta\equiv1-\frac{1}{2S_a}\ ,\quad \eta'\equiv1-\frac{1}{2S_b}\ .$$

Defining the retarded Green's functions $\langle\langle a_l^\dagger(t);a_m(t')\rangle\rangle$, $\langle\langle a_l(t);a_m(t')\rangle\rangle$, $\langle\langle b_l^\dagger(t);a_m(t')\rangle\rangle$, and $\langle\langle b_l(t);a_m(t')\rangle\rangle$ for the two sublattices, respectively, in the usual way,[13] it is easy to obtain the equations of motion for their frequency Fourier transforms $G_{lm}(\omega)$, $G_{lm}'(\omega)$, $F_{lm}(\omega)$, and $F_{lm}'(\omega)$ as

$$\begin{aligned}
&\left[\hbar\omega+2D_l S_a\eta+\sum_j J_{lj}S_b\right]G_{lm}(\omega)=-\sqrt{S_aS_b}\sum_j J_{lj}F'_{jm}(\omega)+2S_a\eta^{1/2}F_l G'_{lm}(\omega)-\frac{\delta_{lm}}{2\pi}\ ,\\
&\left[\hbar\omega-2D_l S_a\eta-\sum_j J_{lj}S_b\right]G'_{lm}(\omega)=\sqrt{S_aS_b}\sum_j J_{lj}F_{jm}(\omega)-2S_a\eta^{1/2}F_l G_{lm}(\omega)\ ,\\
&\left[\hbar\omega+2D'_l S_b\eta'+\sum_i J_{il}S_a\right]F_{lm}(\omega)=-\sqrt{S_aS_b}\sum_i J_{il}G'_{im}(\omega)+2S_b\eta'^{1/2}F'_l F'_{lm}(\omega)\ ,\\
&\left[\hbar\omega-2D'_l S_b\eta'-\sum_i J_{il}S_a\right]F'_{lm}(\omega)=\sqrt{S_aS_b}\sum_i J_{il}G_{im}(\omega)-2S_b\eta'^{1/2}F'_l F_{lm}(\omega)\ .
\end{aligned}\tag{13}$$

We assume the anisotropy parameters $D_i=D_s$ and $F_i=F_s$ if site i is in the surface layer; otherwise, $D_i=D$, $F_i=F$, $D'_j=D'$, and $F'_j=F'$ for all layers. We also assume $J_{ij}=J$, except $J_{ij}=J_s$ if both spins are in the surface layer.

By use of the two-dimensional Fourier transform on a square lattice,[3] the set of coupled equations (13) of motion can be rewritten in terms of the matrix representations as

$$\begin{aligned}
&(\Omega\underline{I}+\underline{A})G(\mathbf{K}_\parallel,\omega)=\underline{B}G'(\mathbf{K}_\parallel,\omega)-\underline{C}F'(\mathbf{K}_\parallel,\omega)-\lambda\underline{I}\ ,\\
&(\Omega\underline{I}-\underline{A})G'(\mathbf{K}_\parallel,\omega)=-\underline{B}G(\mathbf{K}_\parallel,\omega)+\underline{C}F(\mathbf{K}_\parallel,\omega)\ ,\\
&(\Omega\underline{I}+\underline{A}')F(\mathbf{K}_\parallel,\omega)=\underline{B}'F'(\mathbf{K}_\parallel,\omega)-\underline{C}G'(\mathbf{K}_\parallel,\omega)\ ,\\
&(\Omega\underline{I}-\underline{A}')F'(\mathbf{K}_\parallel,\omega)=-\underline{B}'F(\mathbf{K}_\parallel,\omega)+\underline{C}G(\mathbf{K}_\parallel,\omega)\ ,
\end{aligned}\tag{14}$$

with

$$\underline{A}=\begin{bmatrix} d_s & 0 & 0 & 0 & \cdots\\ 0 & d_2 & 0 & 0 & \cdots\\ 0 & 0 & d & 0 & \cdots\\ 0 & 0 & 0 & d & \cdots\\ \vdots & \vdots & \vdots & \vdots & \ddots\end{bmatrix},$$

$$\underline{B}=\begin{bmatrix} f_s & 0 & 0 & 0 & \cdots\\ 0 & f & 0 & 0 & \cdots\\ 0 & 0 & f & 0 & \cdots\\ 0 & 0 & 0 & f & \cdots\\ \vdots & \vdots & \vdots & \vdots & \ddots\end{bmatrix},$$

$$\underline{A}'=\begin{bmatrix} d_1 & 0 & 0 & 0 & \cdots\\ 0 & d_3 & 0 & 0 & \cdots\\ 0 & 0 & d_1 & 0 & \cdots\\ 0 & 0 & 0 & d_1 & \cdots\\ \vdots & \vdots & \vdots & \vdots & \ddots\end{bmatrix},$$

$$\underline{B}'=\begin{bmatrix} f' & 0 & 0 & 0 & \cdots\\ 0 & f' & 0 & 0 & \cdots\\ 0 & 0 & f' & 0 & \cdots\\ 0 & 0 & 0 & f' & \cdots\\ \vdots & \vdots & \vdots & \vdots & \ddots\end{bmatrix},$$

$$\underline{C}=\gamma_K\begin{bmatrix} 0 & 1 & 0 & 0 & \cdots\\ J_s/J & 0 & 1 & 0 & \cdots\\ 0 & 1 & 0 & 1 & \cdots\\ 0 & 0 & 1 & 0 & \cdots\\ \vdots & \vdots & \vdots & \vdots & \ddots\end{bmatrix},$$

$$\underline{I}=\begin{bmatrix} 1 & 0 & 0 & 0 & \cdots\\ 0 & 1 & 0 & 0 & \cdots\\ 0 & 0 & 1 & 0 & \cdots\\ 0 & 0 & 0 & 1 & \cdots\\ \vdots & \vdots & \vdots & \vdots & \ddots\end{bmatrix},$$

where

$$\begin{aligned}
&W=4JS_aS_b\ ,\\
&\Omega=\hbar\omega/W\ ,\\
&d_s=(2DS_a+4JS_b)/W\ ,\\
&d=(2DS_a+8JS_b)/W\ ,\\
&d_1=(2D'S_b+8JS_b)/W\ ,\\
&d_2=[2DS_a+4(J+J_s)S_b]/W\ ,\\
&d_3=[2D'S_b+4(J+J_s)S_a]/W\ ,\\
&f_s=2S_a\eta^{1/2}F/W\ ,\\
&f=2S_a\eta^{1/2}F/W\ ,\\
&f'=2S_b\eta'^{1/2}F'/W\ ,\\
&\lambda=1/(2\pi W)\ ,\\
&\gamma_K=\cos(K_xa_0/2)\cos(K_ya_0/2)\ ,
\end{aligned}\tag{15}$$

$\mathbf{K}_\parallel=(K_x,K_y)$ is a two-dimensional wave vector parallel to the surface, and a_0 is a lattice constant.

In the case of the ferromagnet with nonuniaxial anisotropy, the Green's functions $F_{lm}(\omega)$ and $F'_{lm}(\omega)$ cancel, from the first two equations of Eq. (14). This result is consistent with that of other authors.[7]

From the four coupled equations of Eq. (14), carrying out some algebraic manipulation, we obtain

$$\begin{aligned}
G(\mathbf{K}_\parallel,\omega)=-\lambda[\Omega\underline{I}+\underline{A}+\underline{CMC}\\
-(\underline{B}-\underline{CNC})(-\Omega\underline{I}+\underline{A}-\underline{CPC})^{-1}\\
\times(\underline{B}-\underline{CNC})]^{-1}\underline{I}\ ,
\end{aligned}\tag{16}$$

with

$$\underline{M}=[(\Omega\underline{I}-\underline{A}')+\underline{B}'(\Omega\underline{I}+\underline{A}')^{-1}\underline{B}']^{-1}\ ,$$

$$\underline{N}=[(\Omega\underline{I}-\underline{A}')+B'(\Omega\underline{I}+\underline{A}')^{-1}\underline{B}']^{-1}\underline{B}'(\Omega\underline{I}+\underline{A}')^{-1}\ ,$$

$$\underline{P}=[(\Omega\underline{I}+\underline{A}')+\underline{B}'(\Omega\underline{I}-\underline{A}')^{-1}\underline{B}']^{-1}\ .$$

The surface spin-wave spectrum can be obtained from the poles of $G(\mathbf{K}_{\parallel},\omega)$ by the equation

$$\det[\Omega\underline{I}+\underline{A}+\underline{CMC} -(\underline{B}-\underline{CNC})(-\Omega\underline{I}+\underline{A}-\underline{CPC})^{-1}(\underline{B}-\underline{CNC})]=0\ . \tag{17}$$

B. Results

It is the multiplications of the tridiagonal matrix C that make it hard to calculate Eq. (17) analytically, so that we have to solve Eq. (17) numerically. We take the number of layers as 10, where the result can be regarded approximately as that of a semi-infinite system.[16]

In Fig. 4 we present the surface spin-wave spectrum for some selected values of anisotropy parameters in the case $J=J_s$ (for simplicity, all the parameters of the anisotropy are assumed to be the same). It is clear that, in the presence of anisotropy, only optical branches can be excited. The frequency of the SSW will become soft in the vicinity of the center of the Brillouin zone, especially in the case of strong anisotropy. If the anisotropy strength is weak enough, there exists a narrow region in the vicinity of the Brillouin-zone boundary where the SSW cannot be excited, while it can appear in the boundary of the Brillouin zone (curves a and b). If the anisotropy strength is very strong, the above phenomenon disappears (curves c and d). We have found that under certain conditions there is a critical value of the anisotropy parameter, below which there is a narrow region in the vicinity of the Brillouin-zone boundary, where the SSW cannot be excited. The critical value of the anisotropy is $1.0J$ in the case $J=J_s$.

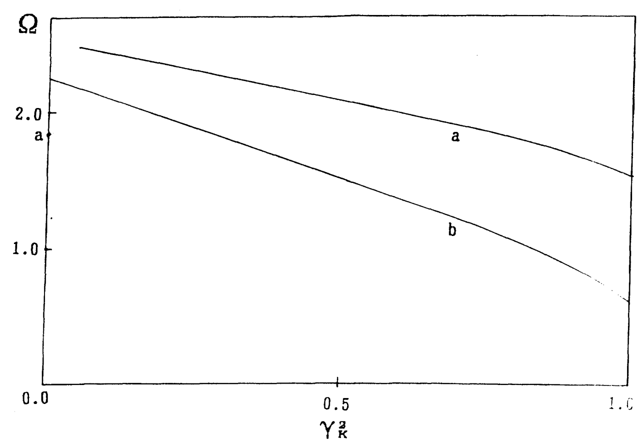

FIG. 5. SSW spectrum with $J=J_s$, $S_a=1.5$, and $S_b=1.0$: $D=D_s=D'=F=F'=0.5J$, $F_s=2.0J$ (curve a); $D=D_s=D'=F=F'=2.0J$, $F_s=0.5J$ (curve b).

The SSW spectra in the case $F_s\neq F,F'$ (here we assume anisotropy parameters to be the same except F_s) are plotted in Fig. 5 with $J=J_s$. We find that the spectra have similar behavior in the case $F_s=F,F'$ (in Fig. 4), except the frequencies are shifted.

In order to examine the effect of the surface-exchange interaction J_s on the SSW spectrum, we examine the cases $J_s/J<1.0$, $J_s/J=1.0$, and $J_s/J>1.0$ in Figs. 6 and 7. We find that an increase in J_s causes a corresponding increase in the frequency of the SSW spectrum. For weak surface-exchange interactions, the frequency of the SSW becomes soft in the vicinity of the center of the Brillouin zone. Comparing Fig. 7 with Fig. 6, we find that the weaker the surface nonuniaxial-anisotropy term, the larger the change of frequency of the SSW in the Brillouin zone.

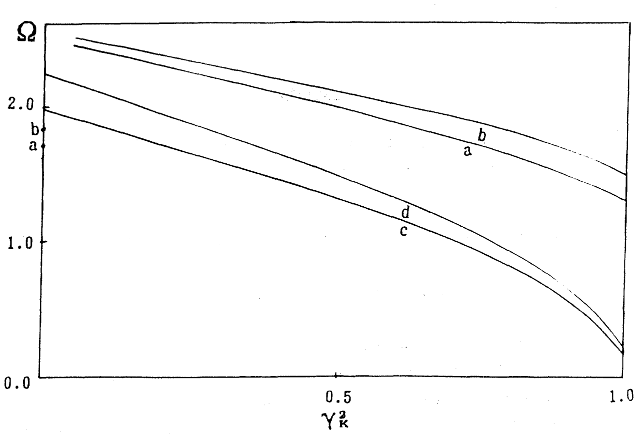

FIG. 4. Dispersion curves of the SSW with $J=J_s$, $S_a=1.5$, and $S_b=1.0$: The different curves correspond to $D=D_s=D'=F=F_s=F'=0.2J$ (curve a), $D=D_s=D'=F=F_s=F'=0.5J$ (curve b), $D=D_s=D'=F=F_s=F'=1.0J$ (curve c), and $D=D_s=D'=F=F_s=F'=2.0J$ (curve d).

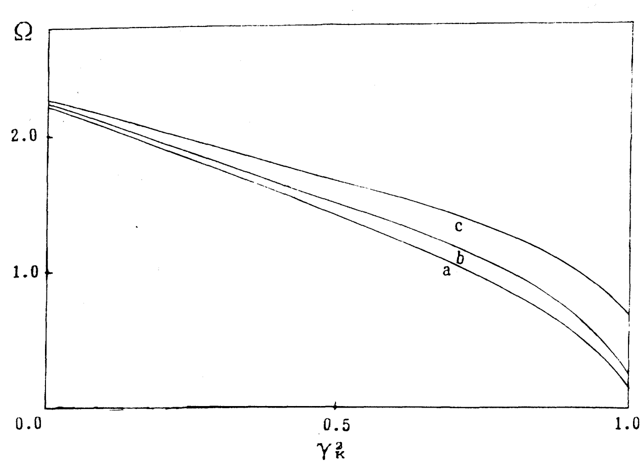

FIG. 6. SSW spectrum with different J_s, $S_a=1.5$, and $S_b=1.0$: $D=D_s=D'=F=F_s=F'=2.0J$, $J_s/J=0.5$ (curve a); $D=D_s=D'=F=F_s=F'=2.0J$, $J_s/J=1.0$ (curve b); and $D=D_s=D'=F=F_s=F'=2.0J$, $J_s/J=1.5$ (curve c).

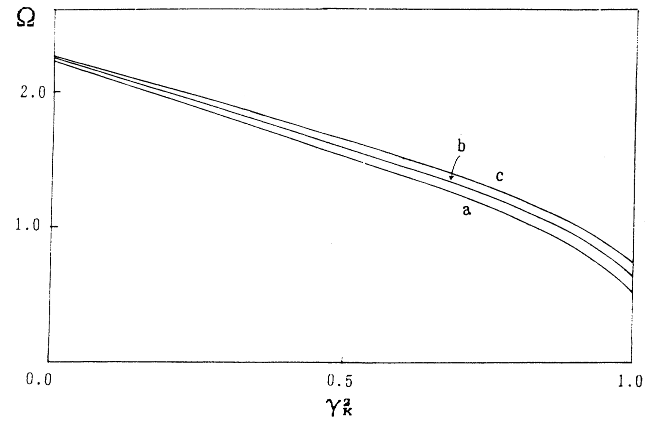

FIG. 7. SSW spectrum with different J_s, $S_a=1.5$, and $S_b=1.0$: $D=D_s=D'=F=F'=2.0J$, $F_s=4.0J$, $J_s/J=0.5$ (curve *a*); $D=D_s=D'=F=F'=2.0J$, $F_s=4.0J$, $J_s/J=1.0$ (curve *b*); and $D=D_s=D'=F=F'=2.0J$, $F_s=4.0J$, $J_s/J=1.5$ (curve *c*).

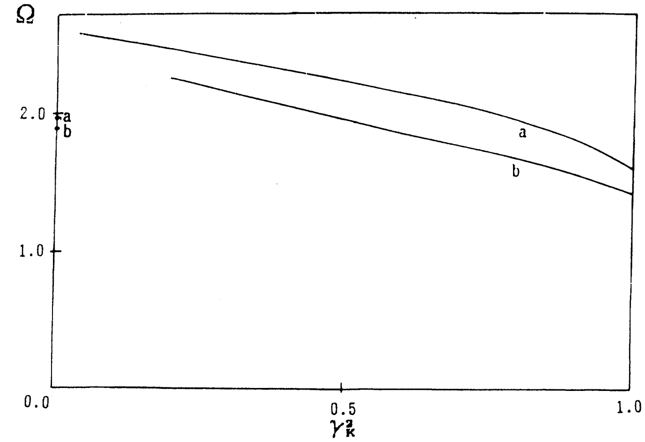

FIG. 8. SSW spectrum with $F=F'=0.0$, $S_a=1.5$, and $S_b=1.0$: $D=D_s=D'=1.0J$, $F_s=2.0J$, $J=J_s$ (curve *a*); $D=D_s=D'=1.0J$, $F_s=2.0J$, $J_s=1.5J$ (curve *b*).

There are systems in which the anisotropy may be nonuniaxial at the surface, while being uniaxial in the bulk,[7] and so we plot this case in Fig. 8. We find that the width of the region where the SSW will disappear in the vicinity of the Brillouin zone changes with the surface-exchange interaction J_s.

IV. CONCLUSIONS

By aid of the Green's-function method, we have examined the surface spin-wave spectrum of a semi-infinite CsCl-type (bcc) ferrimagnet with a single-ion uniaxial and a nonuniaxial anisotropy. We find that the spectrum of the SSW is related to the strength of the anisotropy and, in addition, that only the optical branches of the SSW can be excited in the presence of anisotropy. This can be understood from the fact that the single-ion uniaxial or nonuniaxial anisotropy is favorable to the relative motion of spins for ferrimagnetic two-sublattice structures.

In the uniaxial-anisotropy case, there is a critical value D_{as}^c of the surface-anisotropy parameter when D_{as} is taken as a negative value. Below D_{as}^c, the optical branch will not be excited. This probably is caused by the very strong anisotropy, which is great enough so that the exchange interaction is too weak relatively to excite surface spin waves.

In the nonuniaxial-anisotropy case, we find that the frequency of the SSW will become soft in the vicinity of the center of the Brillouin zone. If the anisotropy at the surface is weak enough, the disappearance of the SSW in a narrow region in the vicinity of the Brillouin-zone boundary may be an interesting phenomenon, which can be expected to be tested by experiments. Under certain conditions, there also exists a critical value of the anisotropy parameter, below which the SSW will not exist in the vicinity of the Brillouin-zone boundary. We have also found that the width of the region of the SSW disappearance changes with the surface-exchange interaction. We believe the method we have used can be applied to the treatment of NaCl-type (fcc) ferrimagnets and superlattice structures with single-ion uniaxial or nonuniaxial anisotropy.

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*Mailing address.

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