RECURRENCE RELATIONS TECHNIQUE IN AN ANTIFERROMAGNETIC SUPERLATTICE

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General dispersion equation of exchange spin waves propagating in a general direction in an antiferromagnetic superlattice is derived by the recurrence relations technique. The elementary unit cell of the superlattice under consideration consists of N different antiferromagnetic layers. The results are illustrated numerically for a particular choice of parameters

Rapid development of modern technologies leads to superlattices (*SLs*) wide application, and this causes an increased interest to their experimental [1-3] and theoretical investigation [4-6]. The study of spin waves is very useful in determining the fundamental parameters which characterize the magnetic systems — anisotropy, exchange coupling, magnetization, surface effects, impurities, dipolar interactions, and magnetic structure. [7]. Therefore theoretical studies of spin-wave excitations in magnetic multilayers, thin films, metamagnets and *SLs* have been the focus of considerable interest for many years, and Green's function method, interface rescaling technique, transfer matrix formalism or recurrence relations technique are used for their studies [8-12]. There have been numerous investigations of the spin waves propagating in the *SLs* composed of two different ferromagnetic or antiferromagnetic materials [13-15]. Comparatively fewer properties of antiferromagnetic SLs have been studied. Existing works on antiferromagnetic multilayers have primarily considered long- wavelength approximations [9,16] or microscopic periodic SL [17,18]. Some general expressions for excitations in discrete N – layered ferromagnetic *SLs* are derived in ref. [19].

In this paper the general dispersion equation of exchange spin waves (short- wavelength limit, where the exchange coupling is dominant) for *SL* with the elementary unit cell consisting of N (=2,3,…) different simple-cubic Heisenberg antiferromagnetic materials is derived by the recurrence relations technique. Recurrence relations technique leads to a compact expression for the spin-wave dispersion relation of the *SL*. The material j (=1,2,…,N) can be characterized by the following bulk parameters: the exchange integral J_j , Lande factors g_j and spin S_j . As indicated in fig.1 the j-th layer consists of n_j atomic layers. The exchange interaction between atoms of two atomic layers at each interface is assumed to be antiferromagnetic, but different from the corresponding bulk couplings. We assume the same lattice parameter α for all the N materials.

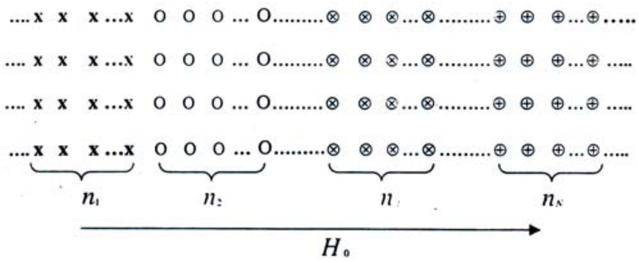

Fig.1. The elementary unit cell of *SL* consisting *N* different simple-cubic Heisenberg antiferrromagnetic materials. The same lattice parameter a is assumed for all the materials. The antiferromagnetic layers consist of n_j (j=1,2,…,N) atomic layers. The layers are infinite in the direction perpendicular to the axes z.

The Hamiltonian of the system can be written in the form

$$H = \sum_{n,\nu,\delta_{11}} J_{n,n}(\vec{S}_{n,\nu}\vec{S}_{n,\nu+\delta_{11}}) + \sum_{n,\nu} J_{n,n+1}(\vec{S}_{n,\nu}\vec{S}_{n+1,\nu}) - \sum_{n,\nu} g_n\mu_B H_n^{(A)}(S^z_{n,\nu a} - S^z_{n,\nu b}) - g_n\mu_B H_0 \sum_{n,\nu}(S^z_{n,\nu a} + S^z_{n,\nu b}) \ , \tag{1}$$

where the first term describes exchange interactions inside atomic layer, the second term describes exchange interactions between neighbouring atomic layers and the last two terms include the Zeeman's energy and magnetic anisotropy energy. Here, n is the index of atomic layer, ν describes the position of a lattice site in this layer and $\delta_{||}$ is the vector of location of the nearest neighbours in the plane. The axis z of the coordinate system is normal to the film interfaces [001] and external field H_0 is assumed to be parallel to the z axis.

Using the equation of motion for the spin operators $S^+_{n,a}(\omega,k_{||})$ and $S^+_{n,b}(\omega,k_{||})$ corresponding to sublattices a and b one finds the following system of equations

$$\begin{cases} \lambda_n^a J_{n,n} S^+_{n,a} - J_{n,n}\gamma(k_{||})S^+_{n,b} - J_{n,n+1}S^+_{n+1,b} - J_{n,n-1}S^+_{n-1,b} = 0 \ , \\ \lambda_n^b J_{n,n} S^+_{n,b} - J_{n,n}\gamma(k_{||})S^+_{n,a} - J_{n,n+1}S^+_{n+1,a} - J_{n,n-1}S^+_{n-1,a} = 0 \ , \end{cases} \tag{2}$$

where λ_n^a, λ_n^b and $\gamma(k_{||})$ are defined as follows $\gamma(k_{||}) = 2(\cos k_x a + \cos k_y a)$,

$$\lambda_n^{a,b} = \left[\pm\left(\omega - g_n\mu_B\left(H_0 \pm H_n^{(A)}\right)\right) - 4J_{n,n}\langle S_n^z\rangle - J_{n,n+1}\langle S_{n+1}^z\rangle - J_{n,n-1}\langle S_{n-1}^z\rangle\right] \Big/ J_{n,n}\langle S_n^z\rangle \ ,$$

the upper sign refers to λ_n^a and the lower one to λ_n^b, respectively. Equation (2) are valid in the low-temperature limit and random-phase-approximation (RPA) $\langle S_{n,a}^z\rangle = -\langle S_{n,b}^z\rangle = \langle S_n^z\rangle$ has already been done.

The system of equations (2) can be solved by recurrence relations technique [13] to relate the spins at the first and second atomic layer of *j*-th and (*j+1*)-th layer of *m*-th elementary unit cell

$$\begin{pmatrix} S^+_{1,(j+1),m,a} \\ S^+_{1,(j+1),m,b} \\ S^+_{2,(j+1),m,a} \\ S^+_{2,(j+1),m,b} \end{pmatrix} = R^{(j,j+1)}(R^{(j)})^{n_j-2} \begin{pmatrix} S^+_{1,j,m,a} \\ S^+_{1,j,m,b} \\ S^+_{2,j,m,a} \\ S^+_{2,j,m,b} \end{pmatrix} = T^{(j)} \begin{pmatrix} S^+_{1,j,m,a} \\ S^+_{1,j,m,b} \\ S^+_{2,j,m,a} \\ S^+_{2,j,m,b} \end{pmatrix} . \qquad (3)$$

the matrices $R^{(j)}$ and $R^{(j,j+1)}$ have the form:

$$R^{(j)} = \begin{pmatrix} 0 & E \\ -E & r^{(j)} \end{pmatrix}, \qquad R^{(j,j+1)} = \frac{J_j}{J_{j,j+1}} \begin{pmatrix} -E & r_{12}^{(j,j+1)} \\ r_{21}^{(j,j+1)} & r_{22}^{(j,j+1)} \end{pmatrix},$$

$$r^{(j)} = \begin{pmatrix} -\gamma(k_{||}) & \lambda_j^b \\ \lambda_j^a & -\gamma(k_{||}) \end{pmatrix}, \quad r_{21}^{(j,j+1)} = \begin{pmatrix} \gamma(k_{||}) & -\lambda_{j+1}^b - \varepsilon_{j+1} \\ -\lambda_{j+1}^a - \varepsilon_{j+1} & \gamma(k_{||}) \end{pmatrix}, \quad r_{12}^{(j,j+1)} = \begin{pmatrix} -\gamma(k_{||}) & \lambda_j^b + \varepsilon_j \\ \lambda_j^a + \varepsilon_j & -\gamma(k_{||}) \end{pmatrix},$$

$$r_{22}^{(j,j+1)} = \begin{pmatrix} \left(\lambda_{j+1}^b + \varepsilon_{j+1}\right)\left(\lambda_j^a + \varepsilon_j\right) + \gamma^2(k_{||}) - J_{j,j+1}^2 / J_j J_{j+1} & -\gamma(k_{||})(\lambda_{j+1}^b + \lambda_j^b + \varepsilon_{j+1} + \varepsilon_j) \\ -\gamma(k_{||})(\lambda_{j+1}^a + \lambda_j^a + \varepsilon_{j+1} + \varepsilon_j) & \left(\lambda_{j+1}^a + \varepsilon_{j+1}\right)\left(\lambda_j^b + \varepsilon_j\right) + \gamma^2(k_{||}) - J_{j,j+1}^2 / J_j J_{j+1} \end{pmatrix},$$

$$\lambda_j^{a,b} = \left[\pm\left(\omega - g_j\mu_B(H_0 \pm H_j^{(A)})\right) - 6J_j\langle S_j^z\rangle\right] \Big/ J_j\langle S_j^z\rangle,$$

$$\varepsilon_j = 1 - J_{j,j+1}\langle S_{j+1}^z\rangle / J_j\langle S_j^z\rangle, \quad \varepsilon_{j+1} = 1 - J_{j+1}\langle S_j^z\rangle / J_{j,j+1}\langle S_{j+1}^z\rangle,$$

and E is twodimensional unit matrix.

The matrix $(R^{(j)})^{n_j-2}$ can be expressed through $R^{(j)}$ using similarity transformation [21].

$$(R^{(j)})^{n_j-2} = \begin{pmatrix} C_{n_j-2} & 0 \\ 0 & C_{n_j-2} \end{pmatrix} R^{(j)} - \begin{pmatrix} C_{n_j-3} & 0 \\ 0 & C_{n_j-3} \end{pmatrix} = \begin{pmatrix} -C_{n_j-3} & C_{n_j-2} \\ -C_{n_j-2} & C_{n_j-1} \end{pmatrix},$$

$$C_{n_j} = U_j \begin{pmatrix} \sin(n_j\theta_2^{(j)}) / \sin(\theta_2^{(j)}) & 0 \\ 0 & \sin(n_j\theta_1^{(j)}) / \sin(\theta_1^{(j)}) \end{pmatrix} U_j^{-1}, \qquad U_j = \begin{pmatrix} \sqrt{\lambda_j^b} & \sqrt{\lambda_j^b} \\ \sqrt{\lambda_j^a} & -\sqrt{\lambda_j^a} \end{pmatrix}. \qquad (4)$$

Here, $\theta_1^{(j)}$ and $\theta_2^{(j)}$ are defined by the expression $2\cos(\theta_{1;2}^{(j)}) = -\gamma(k_{\|}) \pm \sqrt{\lambda_j^a \lambda_j^b}$ with the minus and plus sign, respectively. $\theta_1^{(j)}$ and $\theta_2^{(j)}$ are discussed in ref. [20,21].

The 4x4 matrices $T^{(j)}$ are given by the following expressions

$$T_{11}^{(j)} = \frac{J_j}{J_{j,j+1}}\left[-\alpha_{n_j-1} - \beta_{n_j-2}\varepsilon_j\sqrt{\frac{\lambda_j^a}{\lambda_j^b}}\right], \qquad T_{12}^{(j)} = \frac{J_j}{J_{j,j+1}}\left[-\varepsilon_j\alpha_{n_j-2} - \beta_{n_j-1}\sqrt{\frac{\lambda_j^b}{\lambda_j^a}}\right],$$

$$T_{13}^{(j)} = \frac{J_j}{J_{j,j+1}}\left[\alpha_{n_j} + \beta_{n_j-1}\varepsilon_j\sqrt{\frac{\lambda_j^a}{\lambda_j^b}}\right], \qquad T_{14}^{(j)} = \frac{J_j}{J_{j,j+1}}\left[\varepsilon_j\alpha_{n_j-1} + \beta_{n_j}\sqrt{\frac{\lambda_j^b}{\lambda_j^a}}\right],$$

$$T_{31}^{(j)} = \frac{J_j}{J_{j,j+1}}\left[\gamma(k_{\|})\alpha_{n_j-1} - \left(\lambda_{j+1}^b + \varepsilon_{j+1}\right)\cdot\left(\beta_{n_j-1}\sqrt{\frac{\lambda_j^a}{\lambda_j^b}} + \varepsilon_j\alpha_{n_j-2}\right) + \varepsilon_j\gamma(k_{\|})\beta_{n_j-2}\sqrt{\frac{\lambda_j^a}{\lambda_j^b}} + \frac{J_{j,j+1}^2}{J_jJ_{j+1}}\alpha_{n_j-2}\right],$$

$$T_{32}^{(j)} = \frac{J_j}{J_{j,j+1}}\left[\varepsilon_j\gamma(k_{\|})\alpha_{n_j-2} - \left(\lambda_{j+1}^b + \varepsilon_{j+1}\right)\cdot\left(\varepsilon_j\beta_{n_j-2}\sqrt{\frac{\lambda_j^b}{\lambda_j^a}} + \alpha_{n_j-1}\right) + \sqrt{\frac{\lambda_j^b}{\lambda_j^a}}\left(\gamma(k_{\|})\beta_{n_j-1} + \beta_{n_j-2}\frac{J_{j,j+1}^2}{J_jJ_{j+1}}\right)\right]$$

,

$$T_{33}^{(j)} = \frac{J_j}{J_{j,j+1}}\left[-\gamma(k_{\|})\alpha_{n_j} + \left(\lambda_{j+1}^b + \varepsilon_{j+1}\right)\cdot\left(\beta_{n_j}\sqrt{\frac{\lambda_j^a}{\lambda_j^b}} + \varepsilon_j\alpha_{n_j-1}\right) - \varepsilon_j\gamma(k_{\|})\beta_{n_j-1}\sqrt{\frac{\lambda_j^a}{\lambda_j^b}} - \frac{J_{j,j+1}^2}{J_jJ_{j+1}}\alpha_{n_j-1}\right],$$

$$T_{34}^{(j)} = \frac{J_j}{J_{j,j+1}}\left[-\varepsilon_j\gamma(k_{\|})\alpha_{n_j-1} + \left(\lambda_{j+1}^b + \varepsilon_{j+1}\right)\cdot\left(\varepsilon_j\beta_{n_j-1}\sqrt{\frac{\lambda_j^b}{\lambda_j^a}} + \alpha_{n_j}\right) - \sqrt{\frac{\lambda_j^b}{\lambda_j^a}}\left(\gamma(k_{\|})\beta_{n_j} + \beta_{n_j-1}\frac{J_{j,j+1}^2}{J_jJ_{j+1}}\right)\right],$$

$$T_{21}^{(j)} = T_{12}^{(j)}\{a\to b; b\to a\}, \quad T_{22}^{(j)} = T_{11}^{(j)}\{a\to b; b\to a\}, \quad T_{23}^{(j)} = T_{14}^{(j)}\{a\to b; b\to a\}, \tag{5}$$

$$T_{24}^{(j)} = T_{13}^{(j)}\{a\to b; b\to a\}, \quad T_{41}^{(j)} = T_{32}^{(j)}\{a\to b; b\to a\}, \quad T_{42}^{(j)} = T_{31}^{(j)}\{a\to b; b\to a\},$$

$$T_{43}^{(j)} = T_{34}^{(j)}\{a\to b; b\to a\}, \quad T_{44}^{(j)} = T_{33}^{(j)}\{a\to b; b\to a\},$$

where

$$\alpha_{n_j} = 0.5\left(\frac{\sin(n_j\theta_1^{(j)})}{\sin(\theta_1^{(j)})} + \frac{\sin(n_j\theta_2^{(j)})}{\sin(\theta_2^{(j)})}\right), \qquad \beta_{n_j} = 0.5\left(\frac{\sin(n_j\theta_2^{(j)})}{\sin(\theta_2^{(j)})} - \frac{\sin(n_j\theta_1^{(j)})}{\sin(\theta_1^{(j)})}\right). \tag{6}$$

The matrices $T^{(j)}$ (j=1,2…N) combine to yield transfer matrix $T = T^{(N)}T^{(N-1)}\cdots T^{(1)}$. The matrix elements of $T^{(N)}$ are obtained from the elements of $T^{(j)}$ when $j \to N$ and $j+1 \to 1$. The matrices $T^{(j)}$ (*j*=1,2…*N*) and *T* fulfill the following conditions

$$det(T^{(j)}) = J_j^2 / J_{j+1}^2, \quad detT=1, \; Tr(T)=Tr(T^{1}), \tag{7}$$

where $Tr(T)$ and $Tr(T^{-1})$ are the sum of diagonal elements of *T* and its inverse matrix, respectively.

The eigenvalue problem for the matrix *T* has the form $T\Psi_{1;2}^{\pm} = \eta_{1;2}^{\pm}\Psi_{1;2}^{\pm}$, and the characteristic equation has the following form

$$\eta^4 - Tr(T)\eta^3 + t\eta^2 - Tr(T)\eta + 1 = 0, \tag{8}$$

where

$$t = T_{11}T_{22} - T_{12}T_{21} + T_{11}T_{33} - T_{13}T_{31} + T_{22}T_{33} - T_{23}T_{32} + T_{11}T_{44} - T_{14}T_{41} + T_{22}T_{44} - T_{24}T_{42} + T_{33}T_{44} - T_{34}T_{43},$$

$\eta^{\pm}_{1;2} = exp(\pm iLQ_{1;2})$ are four eigenvalues and $\Psi^{\pm}_{1;2}$ are the corresponding eigenvectors.

Here, $L = \sum_{\sigma=1}^{N} n_\sigma$, La is the periodic distance for the superlattice under consideration.

In general case three different situations are possible:

(i) Either the eigenvalues $\eta^{\pm}_1$ or $\eta^{\pm}_2$ is complex ,

(ii) Both the eigenvalues $\eta^{\pm}_1$ and $\eta^{\pm}_2$ are complex ,

(iii) Both the eigenvalues $\eta^{\pm}_1$ and $\eta^{\pm}_2$ are real.

In every case the following relations are fulfilled

$$\eta^{+}_1 + \eta^{-}_1 + \eta^{+}_2 + \eta^{-}_2 = Tr(T),$$
$$\eta^{+}_{1;2} + \eta^{-}_{1;2} = 2\cos\left(LQ_{1;2}\right) \quad . \quad (9)$$

Using (8) and (9) one obtains the general dispersion equation for exchange spin waves in the superlattices under consideration

$$2\cos(LQ_{1;2}) = \frac{Tr(T)}{2} \pm \sqrt{\left(\frac{Tr(T)}{2}\right)^2 - t + 2} \quad . \quad (10)$$

Equation (10) is the main result of this paper. It can be verified from equation (10) that when all media are identical,

$$J_1 = J_2 = \cdots = J_N = J_{j,j+1} \equiv J_j;$$

$$g_1 = g_2 = \cdots = g_N \equiv g_j;$$

$$\langle S^z_1 \rangle = \langle S^z_2 \rangle = \cdots = \langle S^z_N \rangle \equiv \langle S^z_j \rangle;$$

$$H^{(A)}_1 = H^{(A)}_2 = \cdots = H^{(A)}_N \equiv H^{(A)}_j,$$

$Q_{1;2}$ reduces to $\theta^{(j)}_{1;2}$.

We note that bulk and surface spin waves in finite or semi-infinite system are described by the eigenvalues of the transfer matrix [19]. But in the case of antiferromagnetic structure surface spin waves can not be characterized by a single propagation constant [20,21]. Equation (10) shows that bulk, acoustic and optic spin waves in an antiferromagnetic SL are characterized by two propagation variables Q_1 and Q_2 as an antiferromagnetic constituent are characterized by $\theta^{(j)}_1$ and $\theta^{(j)}_2$. The number of these propagation variables does not depend on the number N of materials consisting of the elementary unit cell of *SL* and the number of atomic layer n_j of the material j $(j = 1,2...N)$.

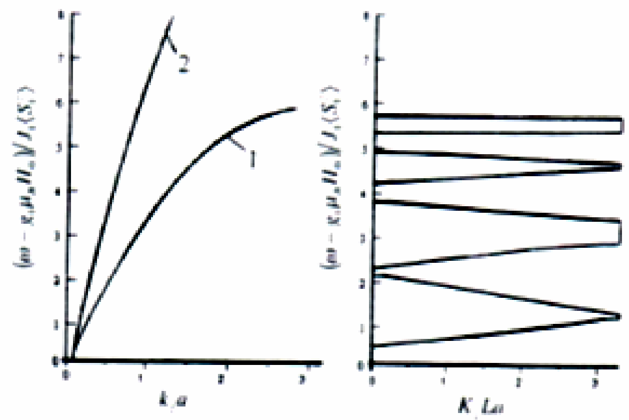

*Fig.2.*Bulk spin–wave dispersion graphs for [001] propagation with parameters $J_2/J_1 = 2$; $g_1 = g_2$; $g_1\mu_B H^{(A)}_1 / J_1\langle S^z_1\rangle = 0.01$; $g_2\mu_B H^{(A)}_2 / J_1\langle S^z_1\rangle = 0.03$;
a) bulk spin – wave dispersion curves for constituents 1 (lower curve) and 2 (upper curve);
b) bulk spin – wave dispersion curve for *SL* when $N=2$; $n_1 = n_2 = 6$; $J/J_1=0.5$.

Although the expression of $cos(Q_{1;2}L)$ is in a complex form one may find the energy range where they are real and $-1 \le cos(Q_{1;2}L) \le 1$. The bulk solution corresponds to the complex eigenvalues of the matrix T in the energy range where $\left|\eta^{\pm}_{1;2}\right| = 1$. We write these eigenvalues in the form $exp(\pm iK_z La)$, where K_z is the normal component of wavevector describing wave propagation in *SL*. For simple numerical illustration we choose the case of *SL* composed of two materials and $k_x = k_y = 0$. Fig.2,a shows the bulk spin-wave dispersion curves of component media 1 and 2 for a particular choice of parameters, while fig.2,b shows the bulk spin-wave dispersion curve of *SL*. The dispersion curves are drawn in the energy range $0 < \left(\omega - g_1\mu_B H_0\right)/J_1\langle S^z_1\rangle < 8$. In the energy range $0 < \left(\omega - g_1\mu_B H_0\right)/J_1\langle S^z_1\rangle < 6$ both components media 1 and 2 have bulk spin-waves. In this energy range the dispersion curve for *SL* exhibits broad pass and narrow stop bands. *SL* spin–wave dispersion curves and the dispersion curves of the component media 1 and 2 move up with increasing anisotropy field.

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ANTİFERROMAQNİT İFRAT QƏFƏSDƏ REKURRENT ƏLAQƏLƏR METODU

Rekurrent əlaqələr metodu ilə antiferromaqnit ifrat qəfəsin oxu boyunca yayılan spin dalğaları üçün ümumi dispersiya tənliyi tapılıb. Baxılan ifrat qəfəsin elementar özəyi *N* sayda müxtəlif antiferromaqnit laydan təşkil olunub. Alınan nəticələr parametrin seçilmiş qiymətləri üçün kəmiyyətcə təsvir olunub.

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ТЕХНИКА РЕКУРРЕНТНЫХ СООТНОШЕНИЙ В АНТИФЕРРОМАГНИТНОЙ СВЕРХРЕШЕТКЕ

Используя технику рекуррентных соотношений, получены общие дисперсионные уравнения для обменных спиновых волн, распространяющихся вдоль оси антиферромагнитной сверхрешетки. Элементарная ячейка рассматриваемой сверхрешетки состоит из *N* различных антиферромагнитных слоев. Приведены численные результаты для выбранных значений параметров.

Received: 14.01.03