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**PHASE DIAGRAMS OF A SPIN-1 ISING SUPERLATTICE
WITH ALTERNATING TRANSVERSE FIELD**

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Abstract

The effects of alternating transverse fields Ω_a and Ω_b on the critical behavior of an alternating spin-1 Ising superlattice are studied within an effective field theory with a probability distribution technique that accounts for the single-site spin correlations. Critical temperatures are calculated as a function of the thickness of the superlattice and the strength of the transverse field. Depending on the values of the transverse fields Ω_a and Ω_b , the critical temperature can increase or decrease with increasing the thickness of the film, such result is not obtained in the uniform transverse field case ($\Omega_a = \Omega_b$). Furthermore, for each thickness L of the film, a long range ordered phase persists at low temperature for selected values of the transverse field Ω_a and arbitrary values of Ω_b . The effects of interlayer and intralayer exchange interactions are also examined.

1 INTRODUCTION

During the last few years much effort has been directed towards the study of the critical phenomena in various magnetic layered structures and superlattices [1-7]. The basic theoretical problem is the examination of the magnetic excitation and the phase transitions in these systems. Magnetic excitations in superlattices were considered in numerous papers (see e.g. [8] for a brief review). Yet, less attention has been paid to the critical behavior and in particular to the critical temperatures in superlattices. Ma and Tasi [9] have studied the variation with modulation wavelength of the Curie temperature for a Heisenberg magnetic superlattice. Their results agree qualitatively with experiments on *Cu/Ni* films [10]. Superlattice structures composed of alternating ferromagnetic and antiferromagnetic layers have been investigated by Hinckey and Mills [11,12], using a localized spin model. Magnetic properties of an alternating magnetic and nonmagnetic superlattice is studied by Benyoussef and Ez-Zahraoui [13] using finite cluster approximation. A sequence of spin transitions is found to be different for superlattices with antiferromagnetic component consisting of an even or odd number of spin layers. In two earlier papers [5, 6] two of the present authors studied the effects of a uniform transverse field and surface magnetism on the critical behavior of an alternating ferromagnetic spin-1/2 Ising superlattice. Our aim in this paper is to study the effects of an alternating transverse field on the critical temperature of a spin-1 Ising superlattice consisting of two ferromagnetic materials with different bulk properties, with a simple cubic structure. In particular, we consider the two constituents A and B with different bulk transition temperatures, i.e. $T_c^A \neq T_c^B$. The interface is in general different in nature from both bulks, even if the bulk critical temperatures are the same. We use the effective field theory with a probability distribution technique in its simplest form [14-15]. This technique is believed to give more exact results than those of the standard mean-field approximation. In section 2 we outline the formalism and derive the equation that determines the transition temperature. Results and discussion are given in section 3. Section 4 is reserved for the conclusion.

2 MODEL AND FORMULATION

We consider an infinite simple cubic superlattice with a unit cell consisting of arbitrary number L of magnetic layers. The Transverse spin-1 Ising Hamiltonian of the system is given by

$$H = - \sum_{n,n'} \sum_{r,r'} J_{nn'} \sigma_{nr}^z \sigma_{n'r'}^z - \sum_n \sum_r \Omega_n \sigma_{nr}^x, \quad (1)$$

where σ_{nr}^z and σ_{nr}^x denote respectively the z and x components of a quantum spin $\vec{\sigma}_{nr}$ of magnitude $\sigma_{nr} = 1$ at site (n, r) , (n, n') , are plane indices and (r, r') are different sites of the planes, and $J_{nn'}$ is the strength of the ferromagnetic exchange interaction which is only plane dependent. We will retain only nearest-neighbor terms. For a fixed configuration of neighbouring

spins of the site (n, r) that the longitudinal and the transverse magnetizations and quadrupolar moments of any spin at site (n, r) are given by,

$$m_{nr\alpha} = \langle \sigma_{nr}^\alpha \rangle = \langle f_{1\alpha}(A, B) \rangle \quad (2)$$

$$q_{nr\alpha} = \langle (\sigma_{nr}^\alpha)^2 \rangle = \langle f_{2\alpha}(A, B) \rangle \quad (3)$$

where $\alpha = z, x$ for the longitudinal and transverse magnetizations and quadrupolar moments respectively and

$$f_{1z}(A, B) = \frac{A}{[A^2 + B^2]^{1/2}} \frac{2 \sinh(\beta [A^2 + B^2]^{1/2})}{1 + 2 \cosh(\beta [A^2 + B^2]^{1/2})} \quad (4)$$

$$f_{2z}(A, B) = \frac{1}{[A^2 + B^2]} \frac{B^2 + (2A^2 + B^2) \cosh(\beta [A^2 + B^2]^{1/2})}{1 + 2 \cosh(\beta [A^2 + B^2]^{1/2})} \quad (5)$$

and

$$f_{1x}(A, B) = f_{1z}(B, A) \quad (6)$$

$$f_{2x}(A, B) = f_{2z}(B, A) \quad (7)$$

with

$$A = \sum_{n'} \sum_{r'} J_{nn'} \sigma_{n'r'}^z, \quad (8)$$

$$B = \Omega_n \quad (9)$$

where $\beta = 1/k_B T$, $\langle \dots \rangle$ indicates the usual canonical ensemble thermal average for a given configuration and the first and second sums run over all possible configurations of atoms envrioning or lying on the (n, r) site, respectively. Each of these configurations can be characterized by numbers of magnetic atoms in the planes $n - 1, n, n + 1$. To perform thermal averaging on the right-hand side of equations (2) and (3) one now follows the general approach described in [14, 16]. Thus with the use of the integral representation method of Dirac δ -distribution, equations (2) and (3) can be written in the form

$$\langle \sigma_{nr}^\alpha \rangle = \int d\omega f_{1\alpha}(\omega, B) \frac{1}{2\pi} \int dt \exp(i\omega t) \prod_{n'r'} \langle \exp(-it J_{n,n'} \sigma_{n'r'}^z) \rangle \quad (10)$$

$$\langle (\sigma_{nr}^\alpha)^2 \rangle = \int d\omega f_{2\alpha}(\omega, B) \frac{1}{2\pi} \int dt \exp(i\omega t) \prod_{n'r'} \langle \exp(-it J J_{n,n'} \sigma_{n'r'}^z) \rangle \quad (11)$$

In the derivation of the equations (10) and (11), the commonly used approximation has been made according to which the multi-spin correlation functions are decoupled into products of the spin averages. Then, as $\langle \sigma_{nr}^\alpha \rangle$ and $\langle (\sigma_{nr}^\alpha)^2 \rangle$ are independent of r , we introduce the longitudinal magnetization and the longitudinal quadrupolar moment of the n -th layer, on the basis of equations (2) and (3), with the use of the probability distribution of the spin variables [13, 14]

$$P(\sigma_{nr}^z) = \frac{1}{2} [(q_{nz} - m_{nz}) \delta(\sigma_{nr}^z + 1) + 2(1 - q_{nz}) \delta(\sigma_{nr}^z) + (q_{nz} + m_{nz}) \delta(\sigma_{nr}^z - 1)] \quad (12)$$

Allowing for the site magnetizations and quadrupolar moments to take different values in each atomic layer parallel to the surfaces of the superlattice, and labeling them in accordance with the layer number in which they are situated, the application of Eqs. (2), (10) and (12) yields the following set of equations for the layer longitudinal magnetizations

$$\begin{aligned}
m_{n\alpha} = & 2^{-N-2N_0} \sum_{\mu=0}^N \sum_{\nu=0}^{N-\mu} \sum_{\mu_1=0}^{N_0} \sum_{\nu_1=0}^{N_0-\mu_1} \sum_{\mu_2=0}^{N_0} \sum_{\nu_2=0}^{N_0-\mu_2} 2^{\mu+\mu_1+\mu_2} C_{\mu}^N C_{\nu}^{N-\mu} \\
& C_{\mu_1}^{N_0} C_{\nu_1}^{N_0-\mu_1} C_{\mu_2}^{N_0} C_{\nu_2}^{N_0-\mu_2} (1-2q_{nz})^{\mu} (q_{nz} - m_{nz})^{\nu} (q_{nz} + m_{nz})^{N-\mu-\nu} \\
& (1-2q_{n-1,z})^{\mu_1} (q_{n-1,z} - m_{n-1,z})^{\nu_1} (q_{n-1,z} + m_{n-1,z})^{N_0-\mu_1-\nu_1} \\
& (1-2q_{n+1,z})^{\mu_2} (q_{n+1,z} - m_{n+1,z})^{\nu_2} (q_{n+1,z} + m_{n+1,z})^{N_0-\mu_2-\nu_2} f_{1\alpha}(y_n, \Omega_n) \quad (13)
\end{aligned}$$

where

$$y_n = J[R(N - \mu - 2\nu) + (2N_0 - \mu_1 - \mu_2 - 2\nu_1 - 2\nu_2)] \quad (14)$$

N and N_0 are the numbers of nearest neighbors in the plane and between adjacent planes respectively ($N = 4$ and $N_0 = 1$ in the case of a simple cubic lattice which is considered here) and C_k^l are the binomial coefficients, $C_k^l = \frac{l!}{k!(l-k)!}$. The periodic conditions of the superlattice has to be satisfied, namely $m_{0\alpha} = m_{L\alpha}$, $m_{L+1,\alpha} = m_{1\alpha}$ and $q_{0\alpha} = q_{L\alpha}$, and $q_{L+1,\alpha} = q_{1\alpha}$. The equations of the longitudinal and transverse quadrupolar moments are obtained by substituting the function $f_{1\alpha}$ by $f_{2\alpha}$ in the expressions of the layer longitudinal and transverse magnetizations respectively. This yields

$$q_{n\alpha} = m_{n\alpha} [f_{1\alpha}(y_n, \Omega_n) \rightarrow f_{2\alpha}(y_n, \Omega_n)] \quad (15)$$

In this work we are interested with the calculation of the ordering near the transition critical temperature. The usual argument that m_{nz} tends to zero as the temperature approaches its critical value, allows us to consider only terms linear in m_{nz} because higher order terms tend to zero faster than m_{nz} on approaching a critical temperature. Consequently, all terms of the order higher than linear terms in eqs. (13) that give the expressions of m_{nz} can be neglected. This leads to the set of simultaneous equations

$$m_{nz} = A_{n,n-1}m_{n-1,z} + A_{n,n}m_{nz} + A_{n,n+1}m_{n+1,z} \quad (16)$$

or

$$A \vec{m}_z = \vec{m}_z \quad (17)$$

where $\vec{m}_z$ is a vector of components $(m_{1z}, m_{2z}, \dots, m_{nz}, \dots, m_{Lz})$ and the matrix A is symmetric and tridiagonal with elements

$$A_{i,j} = A_{i,i}\delta_{i,j} + A_{i,j}(\delta_{i,j-1} + \delta_{i,j+1}) \quad (18)$$

The system of eqs. (17) is of the form

$$M \vec{m}_{nz} = 0 \quad (19)$$

where

$$M_{i,j} = (A_{i,j} - 1) \delta_{i,j} + A_{i,j} (\delta_{i,j-1} + \delta_{i,j+1}) \quad (20)$$

The only non zero elements of the matrix M are given by

$$\begin{aligned} M_{n,n-1} = & 2^{-N-2N_0} \sum_{\mu=0}^N \sum_{\nu=0}^{N-\mu} \sum_{\mu_1=0}^{N_0} \sum_{\nu_1=0}^{N_0-\mu_1} \sum_{\mu_2=0}^{N_0} \sum_{\nu_2=0}^{N_0-\mu_2} \sum_{i=0}^{\nu_1} \sum_{j=0}^{N_0-(\mu_1+\nu_1)} (-1)^i 2^{\mu+\mu_1+\mu_2} \delta_{1,i+j} \quad (21) \\ & C_{\mu}^N C_{\nu}^{N-\mu} C_{\mu_1}^{N_0} C_{\nu_1}^{N_0-\mu_1} C_{\mu_2}^{N_0} C_{\nu_2}^{N_0-\mu_2} C_i^{\nu_1} C_j^{N_0-(\mu_1+\nu_1)} (1-r_n)^{\mu} \\ & (1-r_{n-1})^{\mu_1} (1-r_{n+1})^{\mu_2} r_n^{N-\mu} r_{n-1}^{(N_0-\mu_1)-(i+j)} r_{n+1}^{N_0-\mu_2} f_{1z}(y_n, \Omega_n) \end{aligned}$$

$$\begin{aligned} M_{n,n} = & 2^{-N-2N_0} \sum_{\mu=0}^N \sum_{\nu=0}^{N-\mu} \sum_{\mu_1=0}^{N_0} \sum_{\nu_1=0}^{N_0-\mu_1} \sum_{\mu_2=0}^{N_0} \sum_{\nu_2=0}^{N_0-\mu_2} \sum_{i=0}^{\nu} \sum_{j=0}^{N-(\mu+\nu)} (-1)^i 2^{\mu+\mu_1+\mu_2} \delta_{1,i+j} \\ & C_{\mu}^N C_{\nu}^{N-\mu} C_{\mu_1}^{N_0} C_{\nu_1}^{N_0-\mu_1} C_{\mu_2}^{N_0} C_{\nu_2}^{N_0-\mu_2} C_i^{\nu} C_j^{N-(\mu+\nu)} (1-r_n)^{\mu} \\ & (1-r_{n-1})^{\mu_1} (1-r_{n+1})^{\mu_2} r_n^{N-\mu-(i+j)} r_{n-1}^{(N_0-\mu_1)} r_{n+1}^{N_0-\mu_2} f_{1z}(y_n, \Omega_n) - 1 \quad (22) \end{aligned}$$

$$\begin{aligned} M_{n,n+1} = & 2^{-N-2N_0} \sum_{\mu=0}^N \sum_{\nu=0}^{N-\mu} \sum_{\mu_1=0}^{N_0} \sum_{\nu_1=0}^{N_0-\mu_1} \sum_{\mu_2=0}^{N_0} \sum_{\nu_2=0}^{N_0-\mu_2} \sum_{i=0}^{\nu_2} \sum_{j=0}^{N_0-(\mu_2+\nu_2)} (-1)^i 2^{\mu+\mu_1+\mu_2} \delta_{1,i+j} \\ & C_{\mu}^N C_{\nu}^{N-\mu} C_{\mu_1}^{N_0} C_{\nu_1}^{N_0-\mu_1} C_{\mu_2}^{N_0} C_{\nu_2}^{N_0-\mu_2} C_i^{\nu_1} C_j^{N_0-(\mu_2+\nu_2)} (1-r_n)^{\mu} \\ & (1-r_{n-1})^{\mu_1} (1-r_{n+1})^{\mu_2} r_n^{N-\mu} r_{n-1}^{(N_0-\mu_1)} r_{n+1}^{N_0-\mu_2-(i+j)} f_{1z}(y_n, \Omega_n) \quad (23) \end{aligned}$$

where

$$\begin{aligned} r_n = & 2^{-N-2N_0} \sum_{\mu=0}^N \sum_{\nu=0}^{N-\mu} \sum_{\mu_1=0}^{N_0} \sum_{\nu_1=0}^{N_0-\mu_1} \sum_{\mu_2=0}^{N_0} \sum_{\nu_2=0}^{N_0-\mu_2} 2^{\mu+\mu_1+\mu_2} C_{\mu}^N C_{\nu}^{N-\mu} \\ & C_{\mu_1}^{N_0} C_{\nu_1}^{N_0-\mu_1} C_{\mu_2}^{N_0} C_{\nu_2}^{N_0-\mu_2} (1-2r_n)^{\mu} r_n^{N-\mu} (1-r_{n-1})^{\mu_1} r_{n-1}^{(N_0-\mu_1)} \\ & (1-2r_{n+1})^{\mu_2} r_{n+1}^{N_0-\mu_2} f_{2z}(y_n, \Omega_n) \quad (24) \end{aligned}$$

All the information about the critical temperature of the system is contained in eq. (19). Up to now we did not precise the values of the exchange interactions; the terms in matrix (19) are general ones. In a general case, for arbitrary coupling constants and superlattice thickness the evaluation of the critical temperature relies on the numerical solution of the system of linear equations (19). These equations are fulfilled if and only if

$$\det M = 0 \quad (25)$$

This condition can be satisfied for L different values of the critical temperature T_c . Hereafter, we will take J_{aa} as the unit of the energy, the length is measured in units of the lattice constant and we introduce the reduced exchange couplings $R_1 = J_{bb}/J_{aa}$ and $R_2 = J_{ab}/J_{aa}$. Let us begin with the evaluation of the critical temperature with an example: the critical temperature of the

spin-1 Ising model for the simplest possible "bulk case" of a material A (i.e. $N = 4$, $N_0 = 1$, $J_{i,j} = J_{aa}$, $\Omega_n = \Omega$). Then we can reduce $\det M$ to the following form

$$\det M = \begin{vmatrix} a & b & & & & & & & & & b \\ b & a & b & & & & & & & & \\ & b & a & b & & & & & & & \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ & & & & b & a & b & & & & \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ & & & & & & & b & a & b & \\ & & & & & & & & b & a & b \\ b & & & & & & & & & b & a \end{vmatrix}_{(L,L)} \quad (26)$$

whose values are

$$\det M_{bulk} = \prod_{k=1}^L \left[a + 2b \cos \left(\frac{2\pi(k-1)}{L} \right) \right] \quad (27)$$

where the elements in the above determinant are given by

$$a = M_{n,n} (J_{n,n} = J_{n,n-1} = J_{n,n+1} = J_{aa}, \Omega) \quad (28)$$

$$b = \frac{1}{4} (a + 1) \quad (29)$$

and L in the "bulk" case is an arbitrary number. Now we obtain the critical temperature from the condition given by

$$\det M_{bulk} = 0 \quad (30)$$

We apply the obtained formalism to an alternating magnetic superlattice consisting of atoms of type A and B which alternate as ...ABABAB...AB...in alternating transverse magnetic fields Ω_a, Ω_b respectively. The periodic conditions suggest that we only have to consider one unit cell which interacts with its nearest neighbors via the interlayer coupling. The coupling strength between nearest-neighboring spins in A and B is denoted by J_{aa} and J_{bb} respectively, while J_{ab} stands for the exchange coupling between the nearest-neighbor spins for all successive layers. Let us consider a simple alternating lattice of $2L$ layers $n = 1, 3, 5 \dots 2L - 1$ consist of atoms of type A , whereas layers $n = 2, 4, \dots 2L$ consist of atoms of type B . In this case we can represent $\det M_{ab}$ as

$$\det M_{ab} = \begin{vmatrix} a_1 & b_1 & & & & & & & & & b_1 \\ b_2 & a_2 & b_2 & & & & & & & & \\ & b_1 & a_1 & b_1 & & & & & & & \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ & & & & & & b_2 & a_2 & b_2 & & \\ & & & & & & & b_1 & a_1 & b_1 & \\ b_2 & & & & & & & & & b_2 & a_2 \end{vmatrix}_{(L,L)} \quad (31)$$

whose value is

$$\det M_{ab} = (a_1 a_2)^L \prod_{k=1}^L \left\{ 1 - \frac{2b_1 b_2}{a_1 a_2} \left[1 + \cos \left(\frac{2\pi(k-1)}{L} \right) \right] \right\}, \quad (32)$$

where the elements in the determinant are given by

$$\begin{cases} a_1 = M_{n,n} (J_{n,n} = J_{aa}, J_{n,n-1} = J_{n,n+1} = J_{ab}, \Omega_a) \\ b_1 = M_{n,n-1} (J_{n,n} = J_{aa}, J_{n,n-1} = J_{n,n+1} = J_{ab}, \Omega_a) \\ \quad = M_{n,n+1} (J_{n,n} = J_{aa}, J_{n,n-1} = J_{n,n+1} = J_{ab}, \Omega_a) \end{cases} \quad n = 1, 3, \dots, 2L-1 \quad (33)$$

$$\begin{cases} a_2 = M_{n,n} (J_{n,n} = J_{bb}, J_{n,n-1} = J_{n,n+1} = J_{ab}, \Omega_b) \\ b_2 = M_{n,n-1} (J_{n,n} = J_{bb}, J_{n,n-1} = J_{n,n+1} = J_{ab}, \Omega_b) \\ \quad = M_{n,n+1} (J_{n,n} = J_{bb}, J_{n,n-1} = J_{n,n+1} = J_{ab}, \Omega_b) \end{cases} \quad n = 2, 4, \dots, 2L \quad (34)$$

L is the thickness of the superlattice, it is an arbitrary number. Now we obtain the critical temperature of the system from the condition given by

$$\det M_{ab} = 0. \quad (35)$$

3 Results and discussion

From the numerical solution of eq. (35), the critical temperature of the alternating superlattice is calculated as a function of the reduced exchange interactions R_1 and R_2 . We assume that $R_1 \leq 1$ and denote by $T_c^a/J_{aa} = 3.5186$ and by $T_c^b/J_{aa} = (T_c^a/J_{aa}) R_1$ the bulk critical temperature of a uniform lattice of material A and of material B. In the case of a uniform transverse field ($\Omega_a = \Omega_b$), Fig.1a shows the dependence of the critical temperature T_c/J_{aa} on the reduced interlayer exchange coupling R_2 for various values of the transverse field and $R_1 = 1$. This dependence is quasi linear, in good agreement with the results obtained in the spin-1/2 case [17-18]. From Fig.1b, it is clear that the critical temperature increases with increasing the thickness of the superlattice. Besides this we note that the critical temperature increases with increasing R_2 and/or decreasing the value of the transverse field Ω .

Now, in order to examine the effects of the alternating transverse fields Ω_a and Ω_b , we will neglect the effect of the competition between interlayer and intralayer exchange interactions, for this reason it is practical to choose $R_1 = R_2 = 1$. We note that there is a symmetry between Ω_a and Ω_b (i.e if we change Ω_a by Ω_b and vice versa the results remain the same). The results presented in Fig.2 show the effects of the alternating transverse field on the critical temperature T_c/J_{aa} of the superlattice with a fixed thickness L ($L = 10$). However, T_c decreases with increasing Ω_b . Furthermore, there exists a critical transverse field Ω_a^c , below which the system remains ordered at low temperature for any value of Ω_b (this is called the long range ordered phase), while for Ω_a sufficiently large the system exhibits an ordered-disordered phase transition at very low temperature (in particular at $T = 0$) and the long range order disappears. Such behavior does not occur for very large thickness L and weak strength transverse field Ω_a (Fig.3a), while for Ω_a sufficiently large, and for L large ($L = 32$) the long range ordered phase occurs at low temperature (Fig.3b). These results mean that the critical transverse field Ω_a^c mentioned above depends on the thickness value of the superlattice. Depending on the values of the alternating transverse fields, the critical temperature undergoes two different behaviors as a

function of the thickness of the superlattice. Indeed from Fig.3a it is clear that T_c/J_{aa} decreases with increasing the thickness L of the superlattice for sufficiently weak values of Ω_a and large value of Ω_b , while it increases with increasing the thickness L for Ω_a large and small value of Ω_b . Such results are not obtained in the uniform transverse field case ($\Omega_a = \Omega_b$). We denote that the critical temperature vanishes at the same critical transverse fields Ω_b for any thickness L , which is different than the bulk one (Fig.3b). In Fig.4 we give the behavior of T_c as a function of the thickness of the superlattice from which it is clear that T_c decreases with increasing the thickness L for weak enough Ω_a and large values of Ω_b while it increases with L in the contrary case.

4 Conclusion

We have investigated the effects of alternating transverse fields on the critical behavior of a spin-1 Ising superlattice formed by two alternating ferromagnetic materials using an effective field theory. On one hand it is found that the ordered phase persists at low temperature for sufficiently weak value of (Ω_a/J_{aa}) , and arbitrary value of Ω_b/J_{aa} , such behavior is not obtained in the uniform transverse field case. On the other hand, depending on the values of the transverse field Ω_a and Ω_b , the critical temperature can increase or decrease with increasing the thickness of the superlattice.

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Figure Captions

Fig 1. Critical temperature T_c/J_{aa} as a function of R_2 (a) and the tickness of the superlattice (b). In (b) the number accompanying each curve denotes the value of R_2 , while the solid and dashed lines correspond to $\Omega/J_{aa} = 0, 1$ respectively.

Fig 2. The dependence of the critical temperature T_c/J_{aa} on the transverse field Ω_b/J_{aa} for $L = 10$.

Fig 3. The dependence of the critical temperature T_c/J_{aa} as a function of the transverse field Ω_b for (a) $\Omega_a/J_{aa} = 0.5$ and (b) $\Omega_a/J_{aa} = 2$.

Fig 4. The dependence of the critical temperature T_c/J_{aa} on the thickness L of the finite superlattice.