ELSEVIER

Surface Science 482–485 (2001) 1062–1067

SURFACE SCIENCE

www.elsevier.nl/locate/susc

Giant magnonic band gaps and defect modes in serial stub structures: application to the tunneling between two wires

A. Akjouj [a,*], A. Mir [a,1], B. Djafari-Rouhani [a], J.O. Vasseur [a], L. Dobrzynski [a], H. Al-Wahsh [b], P.A. Deymier [c]

[a] *Laboratoire de Dynamique et Structures des Matériaux Moléculaires, ESA CNRS 8024, UFR de Physique, Université de Lille 1, 59655 Villeneuve d'Ascq, France*

[b] *Faculty of Engineering, Zagazig University, Benha Branch, 11241 Cairo, Egypt*

[c] *Department of Materials Science and Engineering, University of Arizona, Tucson, AZ 85721, USA*

Abstract

In the frame of the long-wavelength Heisenberg model, we investigate the existence of giant gaps in the band structure of a comblike geometry composed of a one-dimensional magnonic waveguide along which N' dangling side branches are grafted at N equidistant sites. These gaps originate not only from the periodicity of the system but also from the resonance states of the grafted branches (which play the role of resonators). The width of these gaps is sensitive to the length of the side branches as well as to the numbers N and N'. The presence of defect branches in the comblike structure can give rise to localized states inside the gaps. These states may have useful applications in the band structure engineering of nanostructure materials.

In the second part of this work, we consider the tunneling between two monomode quantum wires through a coupling device. We give the conditions for selective transfer of a single propagating magnon from one wire to the other, leaving all the neighbor states unaffected. The magnon channel drop tunneling in this system is due to one localized state situated within a gap of the coupling device.

Keywords: Green's function methods; Magnons; Tunneling; Interface states

1. Introduction

Low-dimensional magnets, materials in which magnetism arises from a configuration with a dimensionality less than three, have been shown both theoretically and experimentally to exhibit fascinating collective behaviors [1–4]. During the last decade several studies have addressed the problem of magnon band structures in one-dimensional (1D) [5–9] and two-dimensional (2D) [10] magnetic periodic structures. Most of these studies focus attention on the existence of stop bands in the spin wave spectra of magnetic structures. More recently, Al Wahsh et al. [11] proposed a model of 1D magnonic crystal exhibiting very narrow pass bands separated by large forbidden bands, following similar studies in photonic and electronic band gap materials. This system (called a comb structure) is composed of an infinite 1D waveguide along which an infinite or a

* Corresponding author.
E-mail address: akjouj@lip5rx.univ-lille1.fr (A. Akjouj).

[1] Permanent address: Département de Physique, Faculté des Sciences, Université Moulay Ismaïl, BP 4010, Meknès, Morocco.

0039-6028/01/$ - see front matter
PII: S0039-6028(01)00861-5

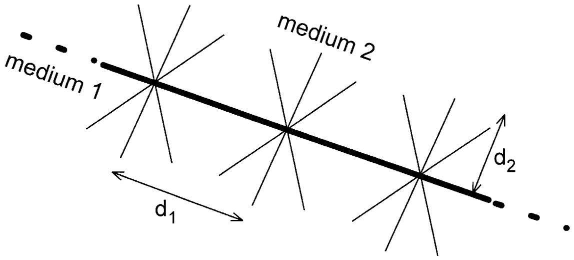

Fig. 1. Schematic of the 1D waveguide studied in the present work. The material media are designated by an index i, with $i = 1$ for the backbone (heavy line) and 2 for the DSB. There are $N'(= 6)$ DSB of length d_2 grafted at equidistant sites separated by a length d_1.

finite set of side branches are grafted periodically (Fig. 1).

Research in the area of high-temperature superconductors has spurred renewed interest into the properties of low-dimensional magnetic systems constituted of networks of quasi-1D chains [12–15]. For instance, one of the most exciting recent developments in this direction has been the fabrication of continuous quasi-1D wires of magnetic materials. Furthermore, advancements in the modern semiconductor technology that allow for the fabrication of nanostructures with controllable chemical composition and geometry such as quantum-wires, -dots, -rings, etc. [15], suggest the possibility in a near future of designing and manufacturing networks of 1D magnetic wires. One can notice that these improvements have been used to design 1D photonic band gap waveguide at the submicrometer scale [16]. These recent developments have encouraged us to continue our theoretical investigation of magnetic excitations in networks composed of 1D continuous magnetic media. In this paper, we first study the magnonic conductance of a 1D waveguide with multiple dangling side branches (MDSB) (see Fig. 1). We show that the band structure of this system may exhibit large band gaps where the propagation of spin waves is forbidden. We also analyze the existence of localized modes associated with defects in comblike structure. We consider, next, the tunneling process through localized resonant states between two monomode quantum wires. We give the conditions for selective transfer of a single propagating magnon from one wire to the other, leaving all the neighboring modes unaffected.

2. Giant band gaps and defect modes in serial stub structures

The serial stub structure with which we are dealing in this section is depicted in Fig. 1. The system is composed of an infinite 1D waveguide (the backbone) along which stars of N' finite side branches are grafted periodically at N equidistant sites. The periodicity d_1 and the length d_2 of the branches characterize the geometry of the system. The media are assumed to be Heisenberg ferromagnets, which means that we are neglecting the dipole–dipole interactions as compared with the exchange contribution to the Hamiltonian. Moreover, we are dealing with long-wavelength magnetic excitations and therefore take use of the continuum approximation of the Heisenberg model (see for details Refs. [7,11]). The backbone and the grafted branches are assumed to be monomode waveguides for the propagation of magnons. With these ingredients, one can derive analytically the dispersion relation of the comblike magnonic structure, as well as the transmission coefficient through a waveguide containing a finite comb. The calculations are performed within a Green's function method in a way similar to those presented in our previous work [11]. In this short communication, we avoid the mathematical details of these calculations and would emphasize the physical discussion of the results.

Although in our analytical calculation, the backbone and the dangling side branches (DSB) can be constituted by different magnetic materials, we shall assume, for the sake of simplicity, that all materials are constituted by the same ferromagnet. Indeed, the occurrence of the magnonic gaps in our structure does not require the use of two different materials, in contrast to the case of usual multilayer structures.

In Fig. 2a we show the first five dispersion curves in the band structure of the infinite comb. We have chosen $d_1 = d_2$, $N' = 1$ and $N \to \infty$. There is a complete absolute gap below the lowest band due to the presence of the external magnetic

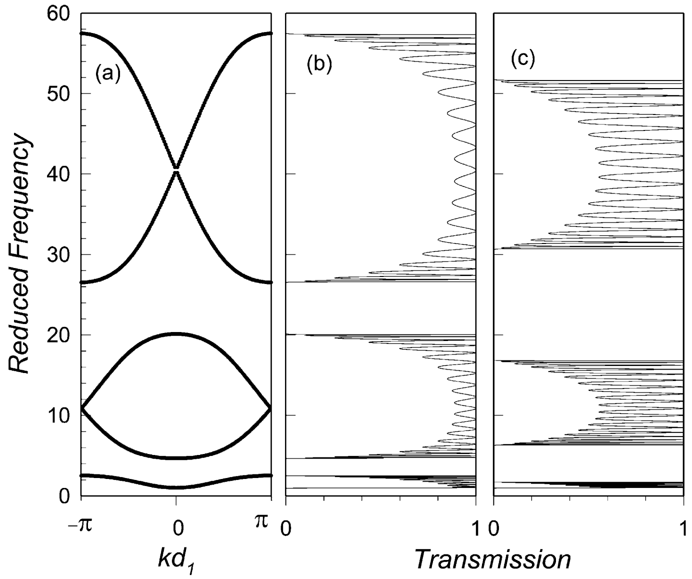

Fig. 2. (a) The first five bands, in the magnonic band structure of the infinite periodic comb. We have chosen $d_1 = d_2$, $N' = 1$ and $N \to \infty$. The plot is given as the reduced frequency versus the dimensionless quantity kd_1 $(-\pi \leqslant kd_1 \leqslant +\pi)$, where k is the modulus of the propagation vector. One observes an absolute gap below the first band due to the presence of the magnetic external field. Transmission coefficient versus the reduced frequency for a wave-guide with (b) $N' = 1$, (c) $N' = 4$ and $N = 10$. The other parameters are the same as in 2a.

field. There exist other absolute gaps, between the first and the second bands, the third and the fourth bands and so on and so forth. The tangential points between the second and the third bands are degenerate points, they appear at $kd_1 = \pi$ and $-\pi$. Another degenerate point is the tangential point between the fourth and the fifth bands that appears at $kd_1 = 0$. The number of oscillations in the transmission factor within the pass bands, which corresponds to the second and the third or to the fourth and fifth bands, has been noted to be unfailingly $2N - 1$. This number is $N - 1$ within the pass band which corresponds to the band which has no tangential points with any other bands. One can notice that increasing N results in turning the pseudo-gaps into full gaps. The convergence to full gaps can be achieved in general for a reasonably small number of sites ($N \geqslant 5$). Next, we discuss the dependence of the transmission factor on the number of DSB. Fig. 2b and c displays the frequency dependence of the transmission for $N' = 1$ and 4, respectively. We call attention to the fact that the width of the pass bands (stop bands) decreases (increases) with increasing number of DSB. We can also note that an increase in N' results in an increase in the amplitude of oscillations of the transmission coefficient.

Let us stress that, unlike in the superlattice structure and 2D composite system where the contrast in physical properties between the constituent materials is a critical parameter in determining the existence of the gaps [5–10], the occurrence of narrow magnonic pass-bands does not require the use of two different materials. In other words, the magnonic structure is tailored within a single homogeneous medium, although the boundary conditions impose the restriction that the waves only propagate in the interior of the waveguides.

Finally, we analyze how the transmission coefficient is affected by the presence of a defect branch at one site of the comb. In particular, the transmission exhibits narrow peaks in the gaps associated with the localized modes. In Fig. 3, we compare the transmission through a comb without defect with that of a defective comb in which the N'

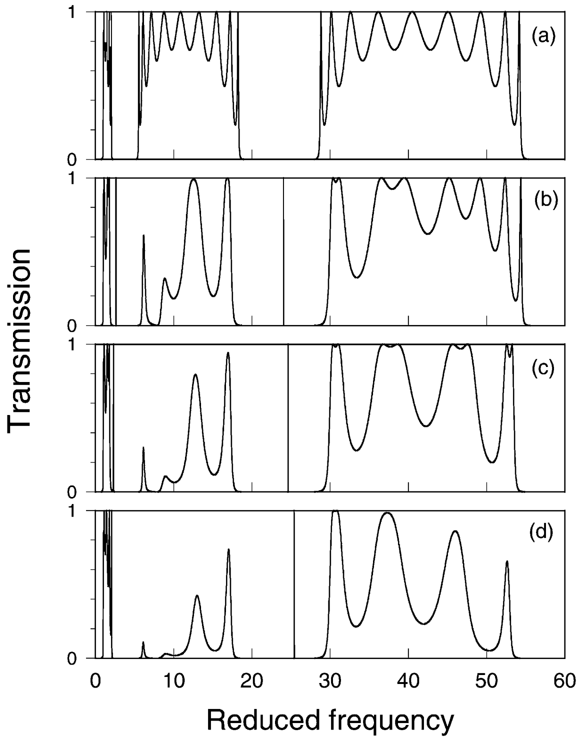

Fig. 3. Transmission spectra versus the frequency for four combs with (b)–(d) and without (a) defect. In the panels (b)–(d), $N'' = 1$, 2 and 4 respectively. The results are illustrated for $N' = 2$, $N = 5$, $d_2 = d_1$, and $d_3 = 0.6d_1$.

DSB at the middle node are replaced by N'' defect DSB of length d_3. The parameters are $N = 5$, $N' = 2$, $d_2 = d_1$, $d_3 = 0.6d_1$ and $N'' = 1$, 2 and 4 in Figs. 3(b)–(d) respectively. The transmission inside a pass band can also be significantly affected by the presence of a defect. For instance, in the example shown in Fig. 3, the transmission is significantly depressed in the second and third pass bands. Let us also notice that the transmission factor in the bands is more depressed as N'' increases. One notes also that the localized modes become more and more confined, i.e., the quality factor of the corresponding peaks increases, with increasing N''.

3. Resonant tunneling between two wires

Resonant tunneling processes can occur between states when they interact through a coupling element which supports localized modes. Of particular interest is the complete channel drop tunneling between 1D continua, i.e. the selective transfer of a single propagating state (i.e. single frequency) from one continuum to the other, leaving all other states unaffected. Examples include the transfer of states between electron waveguides [17], the transfer of photonic waves between dielectric waveguides [18,19], and the transfer of acoustic waves between two slender tubes [20], through a resonator system. However, the resonant tunneling between two magnonic wires was not yet studied.

Inspired by these recent works, we propose a structure (Fig. 4a) that may exhibit this resonant tunneling under certain conditions [20]. This structure, having the symmetry of two mirror planes, is composed of two infinite waveguides coupled through a tunneling system constituted by comblike waveguides. The two continua are the two infinite lines passing by, respectively, points

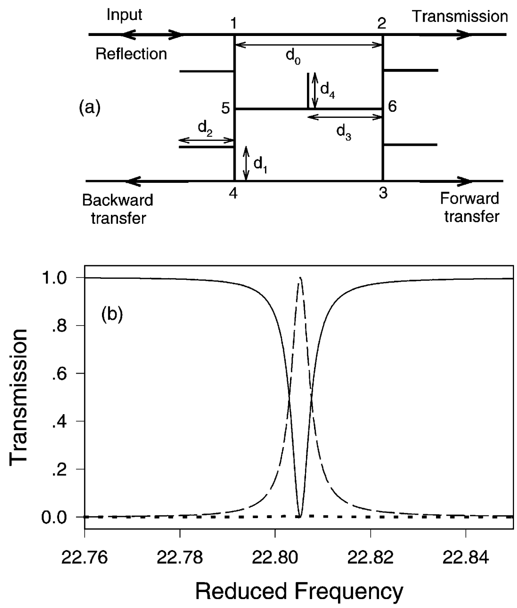

Fig. 4. (a) The structure exhibiting the resonant tunneling. (b) Variation of the intensity of the transmitted signal from site 1 to site 2 (—), and of the transferred signal from site 1 to site 3 (– – –), in the structure shown in (a) versus the frequency. The dots represent the signal intensity in the backward direction, i.e. from site 1 to site 4. These theoretical results were obtained for $d_0 = 4.4d_1$, $d_2 = 1.02d_1$, $d_3 = 2.35d_1$, and $d_4 = 1.01d_1$.

(1,2) and (3,4). The distance between points 1 and 2, called d_0 is the same as that between points 3 and 4. Four identical monomode structures are branched between points (1,5), (5,4), (2,6) and (6,3). These structures have one side stub of length d_2 branched in the middle of the lines of length $2d_1$ situated between the above cited points. Such structures enable to open transmission gaps in the desired frequency range. Between points 5 and 6 is fixed one waveguide of length $2d_3$ with a side stub of length d_4 in its middle. It acts as a resonant cavity having a localized mode within the above mentioned gap.

We give in Fig. 4b the transmission spectra in different channels versus the frequency. We observe both the dip (solid curve) in the direct transmission and the drop in the forward signal (dashed curve). The backward transfer signal represented by the dotted curve, as well as the reflected signal (not shown), are almost completely absent over the entire frequency range. The quality factor of the sharp peaks defined as the ratio between the central frequency and the full width at half maximum is of the order of 4600. A more complete study shows that this quality factor depends strongly on the characteristic lengths.

4. Conclusion

We have investigated the magnonic band structure of 1D comb structures composed of N' MDSB grafted at N equidistant sites along a backbone. There exist large absolute band gaps in the magnonic band structure of an infinite periodic comb with MDSB. The transmission spectrum of spin-waves in a finite comb structure parallels the band structure of the infinite periodic comb. The existence of the gaps in the spectrum is attributed to the joint effect of periodicity and the resonance states of the grafted DSB. In these systems, the gap width is controlled by the numbers N and N' and by the geometrical parameters, including the length of the side branches and the periodicity of the comb. Localized states associated with defects in the comb were observed. These defect modes appear as narrow peaks of strong amplitude in the transmission spectrum. Since magnetic periodic composites have, in general, wide technical applications, it is anticipated that this new class of materials which can be referred to as "magnonic crystals", may turn out to be of significant value for prospective applications.

Finally, we have presented the tunneling between two monomode continua coupled by a monomode structure. The frequency domain where the channel drop tunneling occurs only depends on the characteristic lengths of the constituents of the model system.

At this stage it is worth pointing out again the conditions of validity of the model. In all our calculations we have assumed that the cross-section of the waveguide is small compared to its linear dimension, that is the waveguide may be considered as a 1D medium.

Acknowledgements

A. Mir and H. Al Wahsh would like to acknowledge the hospitality of the Laboratoire de Dynamique et Structures des Matériaux Moléculaires, CNRS ESA 8024, Université de Lille I. A.M.'s works was partially supported by Université Moulay Ismaïl, Meknès, Maroc.

References

[1] M. Greven, R.J. Birgeneau, U.-J. Wiese, Phys. Rev. Lett. 77 (1996) 1865.
[2] S. Chakravarty, Phys. Rev. Lett. 77 (1996) 4446.
[3] D.G. Shelton, A.A. Nersesyan, A.M. Tsvelik, Phys. Rev. B 53 (1996) 8521.
[4] J. Piekarewicz, J.R. Shepard, Phys. Rev. B 57 (1998) 10260.
[5] E.L. Albuquerque, P. Falco, E.F. Sarmento, D.R. Tilley, Solid State Commun. 58 (1986) 41.
[6] L. Dobrzynski, B. Djafari-Rouhani, H. Puszkarski, Phys. Rev. B 33 (1986) 3251.
[7] J. Barnas, Phys. Rev. B 45 (1992) 10427.
[8] L.L. Hinchey, D.J. Mills, Phys. Rev. B 33 (1986) 3359.
[9] L.L. Hinchey, D.J. Mills, Phys. Rev. B 34 (1986) 1689.
[10] J.O. Vasseur, L. Dobrzynski, B. Djafari-Rouhani, H. Puszkarski, Phys. Rev. B 54 (1996) 1043.
[11] H. Al Wahsh, A. Akjouj, B. Djafari-Rouhani, J.O. Vasseur, L. Dobrzynski, P.A. Deymier, Phys. Rev. B 59 (1999) 8709.
[12] A. Blondel, J.P. Meier, B. Boudin, J.P. Ansermet, Appl. Phys. Lett. 65 (1994) 3019.

[13] J. de la Figuera, M.A. Huerta-Garnica, J.E. Prioto, C. Ocal, R. Miranda, Appl. Phys. Lett. 66 (1995) 1006.
[14] W.Z. Li, S.S. Xie, L.X. Qian, B.H. Chang, B.S. Zou, W.Y. Zhou, R.A. Zhao, J. Wang, Science 274 (1996) 1701.
[15] P. Rai-Chaudhry (Ed.), The Handbook of Microlithography, Micromachining, and Microfabrication, SPIE, 1996.
[16] S. Foresi, P.R. Villeneuve, J. Ferrera, E.R. Thoen, G. Steinmeyer, S. Fan, J.D. Joannopoulos, L.C. Kimerling, H.I. Smith, E.P. Ippen, Nature (London) 390 (1997) 143.
[17] C.C. Eugster, J.A. del Alamo, Phys. Rev. Lett. 67 (1991) 3586.
[18] S. Fan, P.R. Villeneuve, J.D. Joannopoulos, Phys. Rev. Lett. 80 (1998) 960.
[19] L. Dobrzynski, B. Djafari-Rouhani, A. Akjouj, J.O. Vasseur, J. Zemmouri, Phys. Rev. B 60 (1999) 10628.
[20] L. Dobrzynski, B. Djafari-Rouhani, A. Akjouj, J.O. Vasseur, J. Zemmouri, Europhys. Lett. 46 (1999) 467.