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L Dobrzynski[1], H Al-Wahsh[1,2], A Akjouj[1,4] and G Hernández-Cocoletzi[1,3]

[1] Institut d'Electronique, de Microélectronique et de Nanotechnologie (IEMN), UMR CNRS 8520, UFR de Physique, Université des Sciences et Technologies de Lille, 59655 Villeneuve d'Ascq Cédex, France
[2] Faculty of Engineering, Benha University, 11241 Cairo, Egypt
[3] Instituto de Física, Universidad Autónoma de Puebla, Apartado Postal J-48, Puebla 72570, Mexico

E-mail: Abdellatif.Akjouj@univ-lille1.fr

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Abstract
Simple nanometric structures enabling the multiplexing and cross-talk transfer of acoustic waves are presented. Such structures are constructed out of two monomode discrete cluster chains and two other clusters situated in between these chains. The clusters interact with one another through the elastic deformation of the substrate on which they are deposited, through the well known energy of interaction between two elastic dipoles. We assume that the cluster mass density is greater than that of the substrate and that the interactions between the clusters are smaller than the corresponding interactions in the substrate. With these assumptions, we may assume that a branch of acoustic waves localized along the chain of clusters exists below the surface Rayleigh wave branch. We show analytically that this simple structure can transfer with selectivity and in one direction one acoustic wavelength from one chain to the other, leaving neighbour acoustic wavelengths unaffected. We give closed form relations enabling us to obtain the values of the relevant physical parameters needed for this multiplexing phenomenon to happen at a chosen wavelength. Finally we illustrate this general theory with an application.

The directional transfer from one waveguide to another has been considered before for elastic waves in macroscopic slender tubes [1] and wires [2] and for optical phonons in atomic chains [3]. Such transfer processes are particularly important in wavelength multiplexing and in telecommunication routing devices [4–7].

A device enabling a directional transfer of an elastic wave of a given wavelength from one wire to the other should let the other neighbour wavelengths travel without perturbation

[4] Author to whom any correspondence should be addressed.

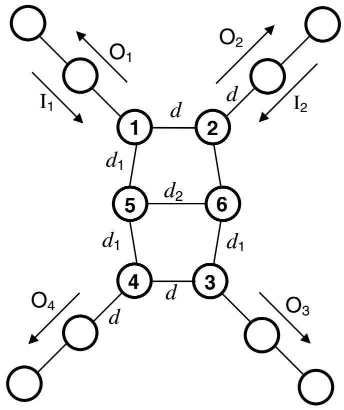

Figure 1. Sketch of the geometry of the nanometric multiplexer considered. It consists of two cluster chains and two other clusters of mass M bound to the substrate by a harmonic force constant K'. They are bound also among themselves by a harmonic force constant β_2 and to clusters (1–4) by harmonic force constants β_1. These force constants are due to the interaction between the clusters due to the elastic dipoles created by the deformations of the substrate. We consider one input I_1 or two inputs $I_1 = I_2$ of out-of-plane acoustic waves and four outputs O_1, O_2, O_3 and O_4.

in the input wire. At the same time this wave of one selected and well defined wavelength is expected to be transferred to the other wire with a phase shift as the only admitted distortion. To meet the above requirements as closely as possible an appropriate coupling geometry should be designed.

In the present paper we describe a nanometric device system which, under certain conditions, makes possible the directional transfer of one acoustic wave with a very good selectivity and directivity. The system is depicted in figure 1. This system is from a physical point of view different from the ones proposed before, as it uses nanoclusters rather than atoms [3] or macroscopic bodies and springs [2]. Here the interactions between the nanoclusters are those between the elastic dipoles created by the deformations of the substrate on which the nanoclusters are adsorbed. Indeed it is well known that when a body of mass m is deposited on a substrate, its weight causes a deformation of the surface of this substrate and then an elastic dipole force. Such substrate mediated interactions occur between any kinds of nanoclusters adsorbed on any kinds of substrates [8]. So in the device proposed in this paper substrate existence is required, although similar devices [2] without a substrate could be created with macroscopic bodies. We will therefore give here only a simple general solution for such a cross-talk device, leaving the choice of specific materials to the experimentalists interested in constructing and testing such a nanometric cross-talk device. Let us be precise that the mathematical derivations of the transmission coefficients for this new physical system are similar to ones given before [3]. This approach uses Green's functions and is equivalent to those of the scattering matrix. Therefore we will give here directly the solutions for the nanometric system considered here.

The structure consists of two cluster chains conducting predominantly the out-of-plane transverse waves. The chains go respectively through points (1, 2) and (3, 4) and two additional clusters of mass M are at points 5 and 6. The distances between points (1, 2) and (3, 4) are Ld, where $L = 1, 2, 3, \ldots$. The chains are characterized by the cluster mass m and the nearest neighbour force constant β related to these transverse vibrations of the chain. This force constant can be obtained as the second derivative of the central energy of interaction between the two elastic dipoles due to the deformation of the substrate. This interaction energy is well known to be inversely proportional to the distance d^3 between the two clusters [8]. The two identical clusters of mass M are assumed to be coupled to the motionless support by a force constant K'. These clusters are also coupled with each other by a force constant β_2 inversely proportional to d_2^5, where d_2 is the distance between these two clusters. The coupling of the wave motion in the cluster chains with the motion of the clusters of mass M is ensured by four harmonic force constants β_1, inversely proportional to d_1^5, where d_1 is the distance between clusters (5, 6) and the clusters (1–4); see figure 1. The system shows two perpendicular mirror symmetry planes. So the main parameters of this model are the ratios β_1/β and β_2/β of the force constants or equivalently d_1/d and d_2/d of the cluster distances, together with the ratios K'/β and M/m. Moreover the simple system presented here can be solved in closed form. This enables us to determine all the parameters necessary for its design by electron lithography for example on a given substrate.

The dispersion relation of the localized transverse modes of the cluster chains is assumed to be [9]

$$m\omega^2 = 2\beta(1 - \cos kd), \tag{1}$$

where ω is the angular frequency and k the propagation vector.

We assumed that the chain clusters are only weakly bound to the substrate and that the influence of this coupling can be neglected in the above dispersion relation, at least for kd smaller than $\pi/2$. This assumption is mostly realistic for clusters physisorbed on the substrate surface. In general and especially in the cases of chemisorption, one can expect a phonon dispersion relation more complicated than the one given by equation (1). However in the long wavelength limit (kd small) the realistic dispersion relation can be matched to one given by this equation via an appropriate choice of β.

In general any incident wave intensity $I_1(kd) = 1$ launched onto the coupling structure, e.g., from the input gate 1, generates, as a result of the scattering processes, the outgoing acoustic wave intensities $O_j(kd)$, $j = 1, 2, 3, 4$ (cf figure 1). The corresponding analytical expressions were given before and illustrated with an application for optical phonons [3].

Here also for these acoustic phonons the total phonon transfer from the input 1 to the output 3, i.e. $O_1 = 0$, $O_2 = 0$, $O_3 = 1$ and $O_4 = 0$, can be realized exactly at the angular frequency ω_0. This frequency and the force constants β, β_1, and β_2 then should fulfil the following conditions:

$$M\omega_0^2 = K' + 2\beta_1 + \beta_2, \tag{2}$$

$$\cos(k_0 Ld) = -\frac{\beta_2}{2\beta_1}, \tag{3}$$

and

$$\frac{\sin(k_0 Ld)}{\sin(k_0 d)} = \frac{\beta\beta_2}{\beta_1^2}, \tag{4}$$

where k_0 is the value of k for $\omega = \omega_0$ in equation (1).

The transferred wave has some width in kd around $k_0 d$. If one wishes the corresponding peak in $O_3(kd)$ to be symmetric, then one obtains another condition [1, 3], namely

$$Lk_0 d = (1 + 4n_0)\frac{\pi}{2}, \qquad n_0 = 0, 1, 2, \ldots. \tag{5}$$

However this condition and the ones given by equations (3) and (4) are only fulfilled for $\beta_1 = 0$ and $\beta_2 = 0$. So in what follows we will tolerate a small dissymmetry of the peak in $O_3(kd)$ and a small imprecision on the condition given by equation (5). This is easily managed by adding a small quantity ε to the right-hand side of equation (5) and then calculating β_2/β, β_1/β and K'/β as a function of this ε.

Let us also define the quality factor associated with the bandwidth of the transferred signal by

$$Q(k_0 d) = \frac{k_0 d}{\Delta(k_0 d)}, \tag{6}$$

where $\Delta(k_0 d)$ is the width of this signal for $O_3(kd) = 0.5$.

An approximated value of this quality factor is found to be

$$Q(k_0 d) = (1 + 4n_0)\frac{\pi}{L}\frac{M}{m}\frac{\beta}{\beta_2}\sin\left[(1 + 4n_0)\frac{\pi}{2L}\right]. \tag{7}$$

One can notice that for big values of d_2, β_2 may become very small and then the quality factor $Q(k_0 d)$ will be very big. However in all physical systems some loss mechanisms exist which would prevent the experimental detection of a too high quality peak. This should be taken into account before trying and choosing precise parameters for an experience.

Let us stress also that such a device is expected to work for the whole range of acoustic waves.

To give an illustrative and at the same time realistic example complying with the above assumptions we consider $n_0 = 0$, $L = 1$, $\beta_1/\beta = 0.2$, $\beta_2/\beta = 0.04$, $m = M$, $K'/\beta = 1$. When the influence of the force constants binding the chain clusters to the substrate on the dispersion relation of the chain phonons can be neglected, we can use the $1/d^5$ proportionality between the force constants and the cluster separation distance d and obtain an estimation for the distances $d_1/d = 1.38$ and $d_2/d = 1.90$. This set of parameters is realistic and could be used for any type of material and any size of the clusters, as long as the clusters are weakly bound to the substrate. If that is not the case, one can recalculate, using the above equations, other parameters for an acoustic phonon transfer in a smaller frequency range, where ω is proportional to k.

Figure 2 presents the transmission coefficients $O_3(kd)$ (solid line), $O_2(kd)$ (dashed line), $O_4(kd)$ (dotted line) and $O_1(kd)$ (dotted–dashed line) as a function of the reduced wavevector kd. One remarks that the dissymmetry with respect to $kd = \pi/2$ is negligible. The peak in the transmission coefficient $O_3(kd)$ shows a width at half-maximum of the order predicted by equation (7). In this figure $O_2(kd)$ is basically constant and equal to 1 after the dip due to the transfer. This result comes from the parameters used in this calculation, but remains for other possible parameter sets as long as the analytical conditions given above are satisfied with a good precision and the chosen quality factor is not too low.

Now with two inputs of intensity $I_1(kd) = I_2(kd) = 1$ at gates 1 and 2, by linear superpositions of the amplitudes the output transmission probabilities can also be obtained [2].

In other words, two transverse acoustic waves of particular propagation vector k_0 are cross-transferred through the structure to gates 3 and 4, respectively. This 'cross-talk' effect is illustrated in figure 3 for the same parameters as were used in figure 2.

The results of the present paper show that the simple structure presented here can realize transverse acoustic wave multiplexing and also cross-transfer of two acoustic waves, respectively from gate 1 to gate 3 and from gate 2 to gate 4. Moreover, the above derived closed form expressions enable us to find easily the optimal parameters for the desired device, enabling us to engineer it at will for specific applications. Although this system does not need to be nanometric in order to operate, it is particularly well adapted for nanoscale technologies. Indeed deposition of nanoclusters on different kinds of substrates is of current interest for such technologies. This system could be excited by surface wave techniques, as is done currently in many telecommunication devices [10].

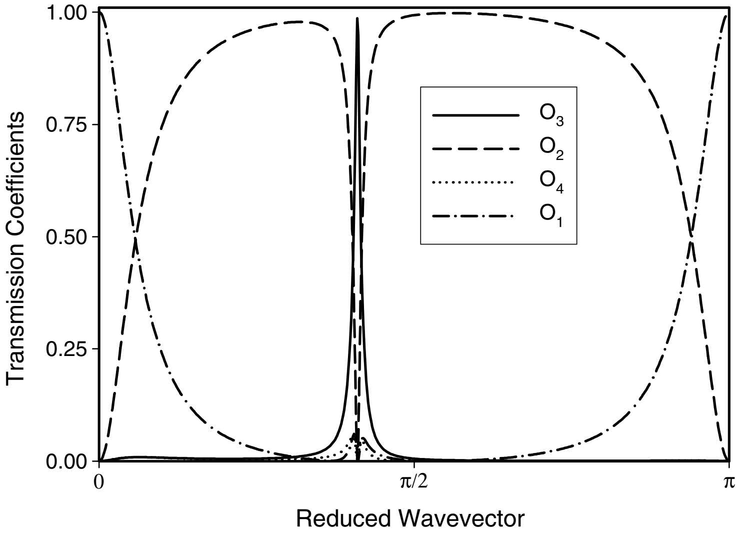

Figure 2. The transmission coefficients $O_3(kd)$ (solid line), $O_2(kd)$ (dashed line), $O_4(kd)$ (dotted line) and $O_1(kd)$ (dotted–dashed line) as a function of kd for $n_0 = 0$, $L = 1$, $\beta_1/\beta = 0.2$, $\beta_2/\beta = 0.04$, $m = M$, $K'/\beta = 1$ with one single input $I_1 = 1$.

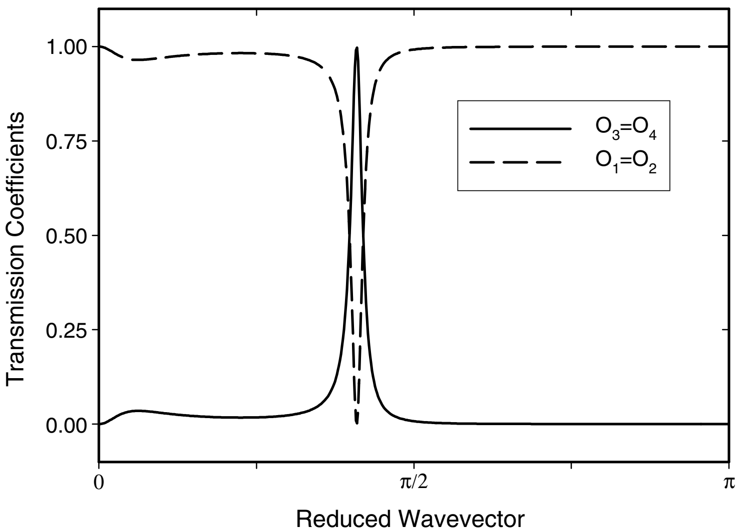

Figure 3. Output signal intensities $O_1(kd) = O_2(kd)$ (dashed line) and $O_3(kd) = O_4(kd)$ (solid line) as a function of kd for the same parameters as in figure 2 when two inputs of intensity $I_1(kd) = I_2(kd) = 1$ at gates 1 and 2 are simultaneously present.

In this paper, we assumed that an appropriate acoustic transducer may excite only 'out-of-plane' transverse phonons in the cluster chain. We neglected the mode conversion of phonons which may appear within the cross-talk device. This should be addressed in future investigations. We try mostly to stress that with the help of nanoclusters, it is possible to construct such simple nanometric cross-talk devices.

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