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Abstract

We consider the homogenization of a system of second-order equations with a large potential in a periodic medium. Denoting by ϵ the period, the potential is scaled as ϵ^{-2}. Under a generic assumption on the spectral properties of the cell problem, we prove that the solution can be factorized as the product of a fast oscillating cell eigenfunction and of a slowly varying solution of a scalar second-order equation. This result applies to various types of equations such as parabolic, hyperbolic or eigenvalue problems, as well as fourth-order plate equation. We also prove that for well-prepared initial data concentrating at the bottom of a Bloch band the resulting homogenized tensor depends on

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the chosen Bloch band. Our method is based on a combination of classical homogenization techniques (two-scale convergence and suitable oscillating test functions) and of Bloch waves decomposition.

1 Introduction

We study the homogenization of evolution problems for a singularly perturbed second order elliptic system with periodically oscillating coefficients. To fix ideas, let us consider the following parabolic problem

$$\begin{cases} \dfrac{\partial u_\epsilon}{\partial t} - \operatorname{div}\left(A\left(\dfrac{x}{\epsilon}\right)\nabla u_\epsilon\right) + \left(\epsilon^{-2}c\left(\dfrac{x}{\epsilon}\right) + d\left(x, \dfrac{x}{\epsilon}\right)\right) u_\epsilon = 0 & \text{in } \Omega \times (0,T), \\ u_\epsilon = 0 & \text{on } \partial\Omega \times (0,T), \\ u_\epsilon(t=0,x) = u_\epsilon^0(x) & \text{in } \Omega, \end{cases} \tag{1}$$

where $\Omega \subset \mathbb{R}^N$ is an open set and $T > 0$ a final time. The unknown $u_\epsilon(t,x)$ is a vector-valued function from $\Omega \times (0,T)$ into $\mathbb{R}^K$. The coefficients $A(y)$, $c(y)$ and $d(x,y)$ are real and bounded functions defined for $x \in \Omega$ and $y \in \mathbb{T}^N$ (the unit torus). Furthermore, the tensor $A(y)$ is symmetric, uniformly positive definite, while $c(y)$ and $d(x,y)$ are symmetric with no positivity assumption. The parabolic equation (1) is just an example: other evolution problems of interest covered by this paper are the wave equation, parabolic fourth-order equations, or spectral problems. A generalization to the Schrödinger equation is the topic of another work [9]. The scalar case of (1) (i.e. $K = 1$ and u_ϵ is a real-valued function) is well understood (see e.g. [4], [7], [8], [21], [28]) and the goal of this paper is to solve the case of systems of several coupled equations. However, the method, as well as some results, are very different in the system case. In order to convince the reader, we first describe the main results and ideas of proof in the scalar case.

For $K = 1$ introduce the first eigencouple of the spectral cell problem

$$-\operatorname{div}_y\left(A(y)\nabla_y\psi_1\right) + c(y)\psi_1 = \lambda_1\psi_1 \quad \text{in } \mathbb{T}^N, \tag{2}$$

which, by the Krein-Rutman theorem, is simple and satisfies $\psi_1(y) > 0$ in $\mathbb{T}^N$. One can interpret physically the first eigenvalue λ_1 as a measure of the balance between the diffusion and potential terms. Since ψ_1 does not vanish, the unknown can be changed by writing a so-called factorization principle

$$v_\epsilon(t,x) = e^{\frac{\lambda_1 t}{\epsilon^2}} \frac{u_\epsilon(t,x)}{\psi_1\left(\frac{x}{\epsilon}\right)}, \tag{3}$$

and one check easily after some algebra that the new unknown v_ϵ is a solution of a simpler equation

$$\begin{cases} \psi_1^2\left(\frac{x}{\epsilon}\right)\frac{\partial v_\epsilon}{\partial t} - \operatorname{div}\left((\psi_1^2 A)\left(\frac{x}{\epsilon}\right)\nabla v_\epsilon\right) + (\psi_1^2 d)\left(x, \frac{x}{\epsilon}\right) v_\epsilon = 0 & \text{in } \Omega \times (0,T), \\ v_\epsilon = 0 & \text{on } \partial\Omega \times (0,T), \\ v_\epsilon(t=0,x) = \frac{u_\epsilon^0(x)}{\psi_1\left(\frac{x}{\epsilon}\right)} & \text{in } \Omega. \end{cases} \tag{4}$$

The new parabolic equation (4) is simple to homogenize since it does not contain any singularly perturbed term, and we thus obtain the following result.

Theorem 1.1 *Assume that (1) is a scalar problem ($K = 1$). Then, v_ϵ, defined by (3), converges weakly in $L^2((0,T); H_0^1(\Omega))$ to the solution v of the following homogenized problem*

$$\begin{cases} \frac{\partial v}{\partial t} - \operatorname{div}(A^*\nabla v) + d^*(x)\, v = 0 & \text{in } \Omega \times (0,T), \\ v = 0 & \text{on } \partial\Omega \times (0,T), \\ v(t=0,x) = v^0(x) & \text{in } \Omega, \end{cases} \tag{5}$$

where A^* is a constant homogenized tensor and $d^*(x)$ a homogenized coefficient.

It is clear from the above brief summary of the scalar case that the main idea, namely the factorization principle (3), does not usually work in the case of systems, i.e. $K > 1$. Indeed, in general there is no maximum principle, and therefore no Krein-Rutman theorem, for systems. Thus, ψ_1 may change sign and the change of unknowns (3) is meaningless because v_ϵ blows up at some points (see however [4] for a special system for which the maximum principle holds true). Even if we perform a formal computation by assuming that (3) is valid, the system satisfied by v_ϵ has not a simple structure and it is not clear that it admits a homogenized limit, and even so, there is no reason why the homogenized tensor should be coercive.

In order to homogenize (1) in the system case, our main new idea is to use Bloch wave theory. Under a generic simplicity assumption for the first eigenvalue and a non-degenerate quadratic behavior near its minimum (see (9)) we obtain a result similar to Theorem 1.1 (see Theorem 3.2 for details). The two main features are that the homogenized equation is always

scalar and that the cell problem must sometimes be shifted, namely the usual periodicity condition in (2) has to be replaced by a Bloch periodicity condition. Our analysis applies not only to the parabolic problem (1) but also to the corresponding spectral problem and hyperbolic system. Section 2 contains our notations, a brief review of Bloch wave theory and our main assumption. Our main results are stated in Section 3 while the proofs are distributed in Sections 4, 5 and 6.

In Section 7 we also obtain new homogenization results for some specific well-prepared initial data (assuming that $\Omega = \mathbb{R}^N$). More precisely, recall that Bloch wave theory introduces the notion of Bloch bands, corresponding to the range of cell eigenvalues or, in physical terms, to energy levels of Fermi surfaces. Theorem 1.1 is concerned with the first Bloch band (or ground state). If we assume that the initial data u_ϵ^0 is concentrating at the bottom of a higher level Bloch band (see Section 7 for a precise statement), we obtain a convergence result similar to Theorem 1.1 but with a different homogenized tensor (depending on the level of the chosen Bloch band). Even in the scalar case this result is new. In the context of Schrödinger equation it is known as an effective mass theorem (see e.g. [22], [24], [25]). The fact that the homogenized tensor depends on the initial data is very striking in homogenization theory since usually effective properties are proved to be intrinsic in the sense that they do not depend on the domain, the applied forces or source terms, and the initial data.

In Section 8 we show that under a new assumption on the first Bloch eigenvalue a different homogenized limit can be obtained for (1). Indeed, the homogenized problem is a parabolic fourth-order equation.

Finally, Section 9 is devoted to an extension of our previous results to a different model, namely we consider a fourth-order equation. We first obtain homogenized limits similar to those of Section 3 but with a fourth-order operator instead of a second-order one. Then, under a different assumption on the first Bloch eigenvalue, we prove that a second-order homogenized limit can also be obtained (a situation which is symmetric from that in Section 8). Our method could be generalized to other models. In particular, its application to the Schrödinger equation is of paramount interest. However, since much more can be deduced in the Schrödinger case, we address this problem in a separate work [9].

There are several motivations for studying the homogenization of the singularly perturbed system (1). First, (1) is a model of reaction-diffusion equations in periodic media (like a porous medium or a crystal in solid state

physics) and the large potential is classical when studying long time asymptotics. Second, the spectral problem for (1) is an usual model in nuclear reactor physics, the so-called simplified transport equation. This is a set of diffusion equations for the even moments of the neutron flux (moments with respect to the angular velocity variable). One of the main features of this simplified transport system is that it does not satisfy a maximum principle. So our work is the first rigorous study of homogenization for this problem, which is of paramount interest for fast numerical computations in the nuclear industry (see [27] for more details and numerical applications). Third, as a limit case of large potentials we recover perforated domains with periodic holes supporting Dirichlet boundary conditions (take $c = +\infty$ in the holes and $c = 0$ elsewhere). In such a case the term of order ϵ^{-2} disappear from the equation (1) although there is still a singular perturbation due to the presence of Dirichlet holes. The scalar setting, $K = 1$, was studied in [28] and we extend this result to the vector-valued case. One possible application is the study of a composite material with fixed incusions in the context of linear elasticity. Fourth, even in the case when $c \equiv 0$ (i.e. without singular perturbation) our homogenization result for initial data concentrating at the bottom of high level Bloch bands is new and can be seen as a type of corrector result for capturing an initial layer in time in the context of classical homogenization [12] (see Remark 7.4).

2 Notations and Bloch decomposition

We first give our precise notations and assumptions on the coefficients $A(y)$ and $c(y)$ involved in equation (1). Our tensorial notations are the following. Recall that N is the space dimension, and K is the system dimension, i.e. all unknown functions are defined with values in $\mathbb{R}^K$. We adopt the convention that Latin indices i, j belong to $\{1, .., N\}$, i.e. refer to spatial coordinates, while Greek indices α, β vary in $\{1, .., K\}$. The $K \times K$ matrices c and d are symmetric, with entries $c_{\alpha\beta}$, $d_{\alpha\beta}$ respectively, and have no specific positivity properties. The tensor A acts on $K \times N$ matrices. Denoting by $(u_\alpha)_{1\leq\alpha\leq K}$ the components of a vector-valued function u, its gradient is the $K \times N$ matrix ∇u defined by its entries

$$\nabla u = \left(\frac{\partial u_\alpha}{\partial x_i}\right)_{1\leq\alpha\leq K,\ 1\leq i\leq N}, \tag{6}$$

and the product $A\nabla u$ is also a $K \times N$ matrix defined with the Einstein summation convention by

$$A\nabla u = \left(A_{\alpha\beta ij} \frac{\partial u_\alpha}{\partial x_i} \right)_{1\le\beta\le K,\ 1\le j\le N}. \tag{7}$$

The tensor A is symmetric in the sense that

$$A\xi \cdot \xi' = A\xi' \cdot \xi \text{ for any } \xi, \xi' \in \mathbb{R}^{K\times N},$$

and it is uniformly coercive, i.e. there exists $\nu > 0$ such that for a.e. $y \in \mathbb{T}^N$

$$A(y)\xi \cdot \xi \ge \nu|\xi|^2 \text{ for any } \xi \in \mathbb{R}^{K\times N}.$$

We assume that $A(y)$ and $c(y)$ are measurable bounded periodic functions, i.e. their entries belong to $L^\infty(\mathbb{T}^N)$, while $d(x, y)$ is measurable and bounded with respect to x, and periodic continuous with respect to y, i.e. its entries belong to $L^\infty\left(\Omega; C(\mathbb{T}^N)\right)$ (other assumptions are possible).

A formal two-scale asymptotic expansion (in the spirit of [11]) shows that the leading term in the ansatz of u_ϵ is the solution of an equation in the unit cell $\mathbb{T}^N$. Therefore, we need to study a microscopic version of (1). It turns out that the key cell problem is the following Bloch (or shifted) spectral cell equation

$$-(\mathrm{div}_y + 2i\pi\theta)\Big(A(y)(\nabla_y + 2i\pi\theta)\psi_n\Big) + c(y)\psi_n = \lambda_n(\theta)\psi_n \quad \text{in } \mathbb{T}^N, \tag{8}$$

which, as a compact self-adjoint complex-valued operator on $L^2(\mathbb{T}^N)$, admits a countable sequence of real increasing eigenvalues $(\lambda_n)_{n\ge1}$ and normalized eigenfunctions $(\psi_n)_{n\ge1}$ with $\|\psi_n\|_{L^2(\mathbb{T}^N)} = 1$. The dual parameter θ is called the Bloch frequency and it runs in the dual cell of $\mathbb{T}^N$, i.e. by periodicity it is enough to consider $\theta \in \mathbb{T}^N$. We refer to [11], [17] for more details about the Bloch spectral problem (8).

Our main assumption is that there exists a Bloch parameter $\theta_0 \in \mathbb{T}^N$ such that

$$\begin{cases} (i) & \theta_0 \text{ is the unique minimizer of } \lambda_1(\theta) \text{ in } \mathbb{T}^N, \\ (ii) & \lambda_1(\theta_0) \text{ is a simple eigenvalue,} \\ (iii) & \text{the Hessian matrix } \nabla_\theta\nabla_\theta\lambda_1(\theta_0) \text{ is positive definite.} \end{cases} \tag{9}$$

Remark 2.1 *In the scalar case, $K = 1$, assumption (9) is satisfied with $\theta_0 = 0$. Indeed, by using the maximum principle, it is easily seen that the minimum of $\lambda_1(\theta)$ is uniquely attained at 0, and then that the Hessian matrix $\nabla_\theta \nabla_\theta \lambda_1(0)$, being equal to the usual homogenized matrix (see e.g. [18]), is positive definite. On the other hand, for any $K \geq 1$ and in the absence of zero-order term, i.e. $c = 0$, it is easy to check that $\theta_0 = 0$ is the unique minimizer of $\lambda_1(\theta)$ (however, $\lambda_1(0)$ may be not simple and/or the Hessian matrix may be not positive definite). In full generality, there always exist a minimizer of $\lambda_1(\theta)$ but it may be non-unique and $\lambda_1(\theta_0)$ has no reason to be simple (although there are some results of generic simplicity in similar contexts, see [1]).*

Remark 2.2 *In a slightly different context, namely for a system of linear elasticity which is not uniformyl elliptic but simply satisfies the Hadamard ellipticity condition (in other words the associed energy is rank-one convex but not convex), there are numerical and physical evidences that the minimal value θ_0 in (9) is not zero [19].*

Remark 2.3 *Assumption (9) can be slightly weakened, see Remarks 4.5 and 4.6.*

Under assumption (9) it is a classical matter to prove that the first eigencouple of (8) is analytic at θ_0. Introducing the operator $\mathbb{A}(\theta)$ defined on $L^2(\mathbb{T}^N)^K$ by

$$\mathbb{A}(\theta)\psi = -(\mathrm{div}_y + 2i\pi\theta)\Big(A(y)(\nabla_y + 2i\pi\theta)\psi\Big) + c(y)\psi - \lambda_1(\theta)\psi, \qquad (10)$$

it is easy to compute the derivatives of (8) for $n = 1$. Denoting by $(e_k)_{1\leq k\leq N}$ the canonical basis of $\mathbb{R}^N$, the first derivative satisfies

$$\mathbb{A}(\theta)\frac{\partial \psi_1}{\partial \theta_k} = 2i\pi e_k A(y)(\nabla_y + 2i\pi\theta)\psi_1 + (\mathrm{div}_y + 2i\pi\theta)\left(A(y)2i\pi e_k\psi_1\right) + \frac{\partial \lambda_1}{\partial \theta_k}(\theta)\psi_1, \qquad (11)$$

and the second derivative is

$$\begin{aligned}\mathbb{A}(\theta)\frac{\partial^2\psi_1}{\partial\theta_k\partial\theta_l} &= 2i\pi e_k A(y)(\nabla_y + 2i\pi\theta)\frac{\partial\psi_1}{\partial\theta_l} + (\mathrm{div}_y + 2i\pi\theta)\left(A(y)2i\pi e_k\frac{\partial\psi_1}{\partial\theta_l}\right)\\ &+2i\pi e_l A(y)(\nabla_y + 2i\pi\theta)\frac{\partial\psi_1}{\partial\theta_k} + (\mathrm{div}_y + 2i\pi\theta)\left(A(y)2i\pi e_l\frac{\partial\psi_1}{\partial\theta_k}\right)\\ &+\frac{\partial\lambda_1}{\partial\theta_k}(\theta)\frac{\partial\psi_1}{\partial\theta_l} + \frac{\partial\lambda_1}{\partial\theta_l}(\theta)\frac{\partial\psi_1}{\partial\theta_k}\\ &-4\pi^2 e_k A(y)e_l\psi_1 - 4\pi^2 e_l A(y)e_k\psi_1 + \frac{\partial^2\lambda_1}{\partial\theta_l\partial\theta_k}(\theta)\psi_1\end{aligned} \tag{12}$$

For $\theta = \theta_0$ we have $\nabla_\theta\lambda_1(\theta_0) = 0$, thus equations (11) and (12) simplify and we find

$$\frac{\partial\psi_1}{\partial\theta_k} = 2i\pi\zeta_k, \quad \frac{\partial^2\psi_1}{\partial\theta_k\partial\theta_l} = -4\pi^2\chi_{kl}, \tag{13}$$

where ζ_k is the solution of

$$\mathbb{A}(\theta_0)\zeta_k = e_k A(y)(\nabla_y + 2i\pi\theta_0)\psi_1 + (\mathrm{div}_y + 2i\pi\theta_0)\left(A(y)e_k\psi_1\right) \quad \text{in } \mathbb{T}^N, \tag{14}$$

and χ_{kl} is the solution of

$$\begin{aligned}\mathbb{A}(\theta_0)\chi_{kl} = \; & e_k A(y)(\nabla_y + 2i\pi\theta_0)\zeta_l + (\mathrm{div}_y + 2i\pi\theta_0)\left(A(y)e_k\zeta_l\right)\\ &+e_l A(y)(\nabla_y + 2i\pi\theta_0)\zeta_k + (\mathrm{div}_y + 2i\pi\theta_0)\left(A(y)e_l\zeta_k\right)\\ &+e_k A(y)e_l\psi_1 + e_l A(y)e_k\psi_1 - \frac{1}{4\pi^2}\frac{\partial^2\lambda_1}{\partial\theta_l\partial\theta_k}(\theta_0)\psi_1 \quad \text{in } \mathbb{T}^N.\end{aligned} \tag{15}$$

There exists a unique solution of (14), up to the addition of a multiple of ψ_1. Indeed, the right hand side of (14) satisfies the required compatibility condition (i.e. it is orthogonal to ψ_1) because ζ_k is just a multiple of the partial derivative of ψ_1 with respect to θ_k which necessarily exists, see (11). On the same token, there exists a unique solution of (15), up to the addition of a multiple of ψ_1. The compatibility condition of (15) yields a formula for the Hessian matrix $\nabla_\theta\nabla_\theta\lambda_1(\theta_0)$.

We now recall some results on the Bloch decomposition associated to the spectral problem (8) (see e.g. [11], [17]).

Lemma 2.4 *Let $u(y) \in L^2(\mathbb{R}^N)^K$. Define $\alpha_k(\theta) = \int_{\mathbb{T}^N} u(y) \cdot \overline{\psi}_k(y,\theta) e^{-2i\pi\theta\cdot y} dy$. Then,*

$$u(y) = \sum_{k\geq 1} \int_{\mathbb{T}^N} \alpha_k(\theta)\psi_k(y,\theta) e^{2i\pi\theta\cdot y} d\theta.$$

Furthermore, if $v(y) = \sum_{k\geq 1} \int_{\mathbb{T}^N} \beta_k(\theta)\psi_k(y,\theta) e^{2i\pi\theta\cdot y} d\theta$ in $L^2(\mathbb{R}^N)^K$, we have

$$\int_{\mathbb{R}^N} u(y)\cdot \overline{v}(y)\, dy = \sum_{k\geq 1} \int_{\mathbb{T}^N} \alpha_k(\theta)\overline{\beta}_k(\theta)\, d\theta.$$

In the sequel we shall need a rescaled version of Lemma 2.4 that we now describe. Upon the change of variable $y = \frac{x}{\epsilon}$, we define $u^\epsilon(x) = \epsilon^{-N/2} u(y)$ which satisfies $\|u^\epsilon\|_{L^2(\mathbb{R}^N)^K} = \|u\|_{L^2(\mathbb{R}^N)^K}$. Applying Lemma 2.4 we deduce the following rescaled Bloch transform

$$u_\epsilon(x) = \sum_{k\geq 1} \int_{\epsilon^{-1}\mathbb{T}^N} \alpha_k^\epsilon(\eta)\psi_k(\frac{x}{\epsilon}, \theta_0 + \epsilon\eta) e^{2i\pi\eta\cdot x} e^{2i\pi\frac{\theta_0\cdot x}{\epsilon}} d\eta, \tag{16}$$

with $\eta = \frac{\theta-\theta_0}{\epsilon}$ and $\alpha_k^\epsilon(\eta) = \epsilon^{N/2}\alpha_k(\theta)$. The same orthogonality property holds true

$$\int_{\mathbb{R}^N} u^\epsilon(x)\cdot \overline{v}^\epsilon(x)\, dx = \sum_{k\geq 1} \int_{\epsilon^{-1}\mathbb{T}^N} \alpha_k^\epsilon(\eta)\overline{\beta}_k^\epsilon(\eta)\, d\eta.$$

3 Main results

Let $\Omega \subset \mathbb{R}^N$ be an open set (bounded or not). Let $0 < T < +\infty$ be a final time. We first consider the following parabolic problem

$$\begin{cases} \dfrac{\partial u_\epsilon}{\partial t} - \operatorname{div}\left(A\left(\dfrac{x}{\epsilon}\right)\nabla u_\epsilon\right) + \left(\dfrac{c\left(\frac{x}{\epsilon}\right)}{\epsilon^2} + d\left(x, \dfrac{x}{\epsilon}\right)\right) u_\epsilon = 0 & \text{in } \Omega\times(0,T), \\ u_\epsilon = 0 & \text{on } \partial\Omega\times(0,T), \\ u_\epsilon(t=0,x) = u_\epsilon^0(x) & \text{in } \Omega. \end{cases} \tag{17}$$

The unknown $u_\epsilon(t,x)$ is vector-valued, i.e. it is a function from $(0,T)\times\Omega$ into $\mathbb{R}^K$ with $K \geq 1$. Assuming that the initial data u_ϵ^0 belongs to $L^2(\Omega)^K$ it is a classical result that there exists a unique solution of (17) in $C\left((0,T); L^2(\Omega)^K\right) \cap L^2\left((0,T); H_0^1(\Omega)^K\right)$.

Since the matrix c does not satisfy any positivity property, we can not obtain any a priori estimate directly from (17). On the other hand, the cell spectral problem and assumption (9) indicate that $\lambda_1(\theta_0)$ governs the time decay (or growth, according to its sign) of the solution u_ϵ. Therefore, we first perform a time renormalization in the spirit of the factorization principle (3) and we introduce a new unknown

$$\tilde{u}_\epsilon(t,x) = e^{\frac{\lambda_1(\theta_0)t}{\epsilon^2}} u_\epsilon(t,x), \tag{18}$$

which satisfies

$$\begin{cases} \dfrac{\partial \tilde{u}_\epsilon}{\partial t} - \operatorname{div}\left(A\left(\dfrac{x}{\epsilon}\right)\nabla \tilde{u}_\epsilon\right) + \dfrac{c\left(\frac{x}{\epsilon}\right) - \lambda_1(\theta_0)}{\epsilon^2}\tilde{u}_\epsilon + d\left(x, \dfrac{x}{\epsilon}\right)\tilde{u}_\epsilon = 0 & \text{in } \Omega \times (0,T), \\ \tilde{u}_\epsilon = 0 & \text{on } \partial\Omega \times (0,T), \\ \tilde{u}_\epsilon(t=0,x) = u_\epsilon^0(x) & \text{in } \Omega. \end{cases} \tag{19}$$

Then, we can obtain the following a priori estimate.

Lemma 3.1 *There exists a constant $C > 0$ which does not depend on ϵ (but may depend on T) such that the solution of (19) satisfies*

$$\|\tilde{u}_\epsilon\|_{L^\infty((0,T);L^2(\Omega)^K)} + \epsilon\|\nabla \tilde{u}_\epsilon\|_{L^2((0,T)\times\Omega)^{N\times K}} \leq C\|u_\epsilon^0\|_{L^2(\Omega)^K}. \tag{20}$$

Theorem 3.2 *Assume (9) and that the initial data $u_\epsilon^0 \in L^2(\Omega)^K$ is of the form*

$$u_\epsilon^0(x) = \psi_1\left(\frac{x}{\epsilon}, \theta_0\right) e^{2i\pi\frac{\theta_0\cdot x}{\epsilon}} v^0(x), \tag{21}$$

with $v^0 \in L^2(\Omega)$. The solution of (17) can be written as

$$u_\epsilon(t,x) = e^{-\frac{\lambda_1(\theta_0)t}{\epsilon^2}}\left(\psi_1\left(\frac{x}{\epsilon}, \theta_0\right) e^{2i\pi\frac{\theta_0\cdot x}{\epsilon}} v_\epsilon(t,x) + r_\epsilon(t,x)\right), \tag{22}$$

where r_ϵ is a vector-valued remainder term such that

$$\lim_{\epsilon\to 0}\|r_\epsilon\|_{L^2((0,T)\times\omega)^K} = 0 \text{ for any compact set } \omega \subset \mathbb{R}^N, \tag{23}$$

and v_ϵ is a scalar sequence which converges weakly in $L^2\left((0,T);H^1(\Omega)\right)$ to the solution v of the scalar homogenized problem

$$\begin{cases} \dfrac{\partial v}{\partial t} - \operatorname{div}\left(A^*\nabla v\right) + d^*(x)\, v = 0 & \text{in } \Omega \times (0,T), \\ v = 0 & \text{on } \partial\Omega \times (0,T), \\ v(t=0,x) = v^0(x) & \text{in } \Omega, \end{cases} \tag{24}$$

with $A^* = \frac{1}{4\pi^2}\nabla_\theta\nabla_\theta\lambda_1(\theta_0)$ and $d^*(x) = \int_{\mathbb{T}^N} d(x,y)\psi_1(y)\cdot\overline{\psi}_1(y)\,dy$.

Remark 3.3 *Of course, if Ω is bounded, one can take $\omega = \Omega$ in (23).*

Remark 3.4 *Assumption (21) is not necessary for proving Theorem 3.2. For example, it still holds true with the weaker assumption that $u_\epsilon^0(x)e^{-2i\pi\frac{\theta_0\cdot x}{\epsilon}}$ two-scale converges to $\psi_1(y,\theta_0)v^0(x)$ with $v^0 \in L^2(\Omega)$ (see [2], [23] for the notion of two-scale convergence). Furthermore, for any kind of initial data we can still obtain a similar result, but the homogenized initial condition v^0 is just defined as some type of weak two-scale limit (which may well be zero). In other words, there is no need to have "well-prepared" initial data in Theorem 3.2.*

Remark 3.5 *Theorem 3.2 still holds true if we add to equation (17) a non-linear term of order ϵ^0. Typically, we can add a non-linear term of the type $g(x, \frac{x}{\epsilon}, u_\epsilon)$ where $g(x,y,\xi)$ is an homogeneous of degree one, Lipschitz function with respect to ξ such that*

$$|g(x,y,\xi) - g(x,y,\xi')| \leq C|\xi - \xi'|, \quad g(x,y,t\xi) = tg(x,y,\xi) \quad \forall\, t > 0.$$

In such a case, the homogenized problem (24) has an additional zero-order term which is $g^*(x,v)$ with $g^*(x,v) = \int_{\mathbb{T}^N} g(x,y,\psi_1(y,\theta_0)v)\cdot\overline{\psi}_1(y,\theta_0)\,dy$. Similarly, it is possible to add to (17) a source term of the type

$$f_\epsilon(t,x) = e^{-\frac{\lambda_1(\theta_0)t}{\epsilon^2}} e^{2i\pi\frac{\theta_0\cdot x}{\epsilon}} f\left(t,x,\frac{x}{\epsilon}\right).$$

It yields a source term $f^*(t,x) = \int_{\mathbb{T}^N} f(t,x,y)\cdot\overline{\psi}_1(y)\,dy$ in the homogenized equation (24).

We now consider the eigenvalue problem in a bounded domain Ω (the case of $\Omega = \mathbb{R}^N$ is also discussed in Section 5)

$$\begin{cases} -\mathrm{div}\left(A\left(\frac{x}{\epsilon}\right)\nabla u_\epsilon\right) + \left(\frac{c\left(\frac{x}{\epsilon}\right)}{\epsilon^2} + d\left(x,\frac{x}{\epsilon}\right)\right)u_\epsilon = \lambda_\epsilon u_\epsilon & \text{in } \Omega, \\ u_\epsilon = 0 & \text{on } \partial\Omega. \end{cases} \tag{25}$$

Since Ω is assumed to be bounded, problem (25) has a discrete spectrum

$$\lambda_1^\epsilon \leq \lambda_2^\epsilon \leq \ldots \leq \lambda_n^\epsilon \ldots \to +\infty,$$

with eigenfunctions denoted by u_k^ϵ, normalized by $\|u_k^\epsilon\|_{L^2(\Omega)^K} = 1$.

Theorem 3.6 *For each $k \geq 1$ we have*

$$\lambda_k^\epsilon = \frac{\lambda_1(\theta_0)}{\epsilon^2} + \mu_k + o(1) \qquad \textit{with } \lim_{\epsilon \to 0} o(1) = 0,$$

and the corresponding eigenvector $u_k^\epsilon(x)$ admits the representation

$$u_k^\epsilon(x) = \psi_1\left(\frac{x}{\epsilon}, \theta_0\right) e^{2i\pi \frac{\theta_0 \cdot x}{\epsilon}} v_k^\epsilon(x) + r_k^\epsilon(x) \tag{26}$$

where

$$\lim_{\epsilon \to 0} \|r_k^\epsilon\|_{L^2(\Omega)^K} = 0, \quad \|v_k^\epsilon\|_{H^1(\Omega)} \leq C, \quad \lim_{\epsilon \to 0} \|v_k^\epsilon\|_{L^2(\Omega)} = 1,$$

and any limit point v_k, as $\epsilon \to 0$, of the scalar sequence v_k^ϵ is a normalized eigenfunction associated to the k-th eigenvalue μ_k of the scalar homogenized spectral problem

$$\begin{cases} -\mathrm{div}\,(A^* \nabla v) + d^*(x) v = \mu v & \textit{in } \Omega, \\ v = 0 & \textit{on } \partial\Omega, \end{cases} \tag{27}$$

with $A^* = \frac{1}{4\pi^2} \nabla_\theta \nabla_\theta \lambda_1(\theta_0)$ and $d^*(x) = \int_{\mathbb{T}^N} d(x,y) \psi_1(y) \cdot \overline{\psi}_1(y)\, dy$.

Furthermore, if μ_k is a simple eigenvalue of (27), the entire sequence v_k^ϵ converges to the homogenized eigenfunction v_k.

Finally we address the following hyperbolic problem

$$\begin{cases} \dfrac{\partial^2 u_\epsilon}{\partial t^2} - \mathrm{div}\left(A\left(\dfrac{x}{\epsilon}\right) \nabla u_\epsilon\right) + \dfrac{c\left(\frac{x}{\epsilon}\right)}{\epsilon^2} u_\epsilon = 0 & \text{in } \Omega \times (0,T), \\ u_\epsilon = 0 & \text{on } \partial\Omega \times (0,T), \\ u_\epsilon(t=0,x) = u_\epsilon^0(x) & \text{in } \Omega, \\ \dfrac{\partial u_\epsilon}{\partial t}(t=0,x) = u_\epsilon^1(x) & \text{in } \Omega. \end{cases} \tag{28}$$

The unknown $u_\epsilon(t,x)$ is vector-valued, i.e. it is a function from $(0,T) \times \Omega$ into $\mathbb{R}^K$ with $K \geq 1$. Assuming that the initial data are $u_\epsilon^0 \in H_0^1(\Omega)^K$ and $u_\epsilon^1 \in L^2(\Omega)^K$, (28) admits a unique solution $u_\epsilon \in C\left([0,T]; H_0^1(\Omega)^K\right) \cap C^1\left([0,T]; L^2(\Omega)^K\right)$. The scalar case $K = 1$ was addressed in [3]. Depending on the sign of the minimal eigenvalue $\lambda_1(\theta_0)$ of the cell problem (8), we obtain different asymptotic behavior for (28). We begin with the case $\lambda_1(\theta_0) = 0$ which does not require any time renormalization.

Theorem 3.7 *Assume (9), $\lambda_1(\theta_0) = 0$ and that the initial data are of the form*

$$\begin{aligned} u_\epsilon^0(x) &= \psi_1\left(\frac{x}{\epsilon}, \theta_0\right) e^{2i\pi\frac{\theta_0\cdot x}{\epsilon}} v^0(x) \in H_0^1(\Omega)^K, \\ u_\epsilon^1(x) &= \psi_1\left(\frac{x}{\epsilon}, \theta_0\right) e^{2i\pi\frac{\theta_0\cdot x}{\epsilon}} v^1(x) \in L^2(\Omega)^K, \end{aligned} \tag{29}$$

with $v^0 \in H_0^1(\Omega)$ and $v^1 \in L^2(\Omega)$. The solution of (28) can be written as

$$u_\epsilon(t,x) = \psi_1\left(\frac{x}{\epsilon}, \theta_0\right) e^{2i\pi\frac{\theta_0\cdot x}{\epsilon}} v_\epsilon(t,x) + r_\epsilon(t,x), \tag{30}$$

where r_ϵ is a vector-valued remainder term such that

$$\lim_{\epsilon\to 0} \|r_\epsilon\|_{L^2((0,T)\times\omega)^K} = 0 \text{ for any compact set } \omega \subset \mathbb{R}^N, \tag{31}$$

and v_ϵ is a scalar sequence which converges weakly in $L^2\left((0,T); H^1(\Omega)\right)$ to the solution v of the scalar homogenized problem

$$\begin{cases} \dfrac{\partial^2 v}{\partial t^2} - \operatorname{div}\left(A^*\nabla v\right) = 0 & \text{in } \Omega\times(0,T), \\ v = 0 & \text{on } \partial\Omega\times(0,T), \\ v(t=0,x) = v^0(x) & \text{in } \Omega, \\ \frac{\partial v}{\partial t}(t=0,x) = v^1(x) & \text{in } \Omega, \end{cases} \tag{32}$$

with $A^* = \frac{1}{4\pi^2}\nabla_\theta\nabla_\theta\lambda_1(\theta_0)$.

When $\lambda_1(\theta_0) \neq 0$, we can not homogenize directly (28). As in the scalar case [3] we must rather perform a time rescaling and consider large times of order ϵ^{-1}. In other words, instead of (28) we now consider

$$\begin{cases} \epsilon^2\dfrac{\partial^2 u_\epsilon}{\partial t^2} - \operatorname{div}\left(A\left(\dfrac{x}{\epsilon}\right)\nabla u_\epsilon\right) + \dfrac{c\left(\frac{x}{\epsilon}\right)}{\epsilon^2} u_\epsilon = 0 & \text{in } \Omega\times(0,T) \\ u_\epsilon = 0 & \text{on } \partial\Omega\times(0,T) \\ u_\epsilon(t=0,x) = u_\epsilon^0(x) & \text{in } \Omega \\ \frac{\partial u_\epsilon}{\partial t}(t=0,x) = u_\epsilon^1(x) & \text{in } \Omega. \end{cases} \tag{33}$$

Let us first assume that $\lambda_1(\theta_0) < 0$. We perform a time renormalization analogous to (18) and we introduce a new unknown

$$\tilde{u}_\epsilon(t,x) = e^{-\frac{\sqrt{-\lambda_1(\theta_0)}t}{\epsilon^2}} u_\epsilon(t,x), \tag{34}$$

which satisfies

$$\begin{cases} \epsilon^2 \dfrac{\partial^2 \tilde{u}_\epsilon}{\partial t^2} + 2\sqrt{-\lambda_1(\theta_0)} \dfrac{\partial \tilde{u}_\epsilon}{\partial t} - \operatorname{div}\left(A\left(\dfrac{x}{\epsilon}\right)\nabla \tilde{u}_\epsilon\right) + \dfrac{c\left(\frac{x}{\epsilon}\right) - \lambda_1(\theta_0)}{\epsilon^2}\tilde{u}_\epsilon = 0 & \text{in } \Omega \times (0,T), \\ \tilde{u}_\epsilon = 0 & \text{on } \partial\Omega \times (0,T), \\ \tilde{u}_\epsilon(t=0,x) = u_\epsilon^0(x) & \text{in } \Omega, \\ \frac{\partial \tilde{u}_\epsilon}{\partial t}(t=0,x) = u_\epsilon^1(x) - \dfrac{\sqrt{-\lambda_1(\theta_0)}}{\epsilon^2} u_\epsilon^0(x) & \text{in } \Omega. \end{cases} \tag{35}$$

In this case we obtain a parabolic homogenized equation.

Theorem 3.8 *Assume (9), $\lambda_1(\theta_0) < 0$ and that the initial data is*

$$u_\epsilon^0(x) = \psi_1\left(\frac{x}{\epsilon}, \theta_0\right) e^{2i\pi \frac{\theta_0 \cdot x}{\epsilon}} v^0(x) \in H_0^1(\Omega)^K, \tag{36}$$

with $v^0 \in H_0^1(\Omega)$, and that $\epsilon^2 u_\epsilon^1(x)$ is bounded in $L^2(\Omega)^K$ while $\epsilon^2 \psi_1\left(\frac{x}{\epsilon}, \theta_0\right) \cdot u_\epsilon^1(x)$ converges weakly to 0 in $L^2(\Omega)$. The solution of (35) can be written as

$$u_\epsilon(t,x) = e^{\frac{\sqrt{-\lambda_1(\theta_0)}t}{\epsilon^2}} \left(\psi_1\left(\frac{x}{\epsilon}, \theta_0\right) e^{2i\pi \frac{\theta_0 \cdot x}{\epsilon}} v_\epsilon(t,x) + r_\epsilon(t,x)\right), \tag{37}$$

where r_ϵ is a vector-valued remainder term such that

$$\lim_{\epsilon \to 0} \|r_\epsilon\|_{L^2((0,T)\times\omega)^K} = 0 \text{ for any compact set } \omega \subset \mathbb{R}^N, \tag{38}$$

and v_ϵ converges weakly in $L^2\left((0,T); H^1(\Omega)\right)$ to the solution v of the scalar homogenized problem

$$\begin{cases} 2\sqrt{-\lambda_1(\theta_0)} \dfrac{\partial v}{\partial t} - \operatorname{div}\left(A^* \nabla v\right) = 0 & \text{in } \Omega \times (0,T), \\ v = 0 & \text{on } \partial\Omega \times (0,T), \\ v(t=0,x) = \frac{1}{2} v^0(x) & \text{in } \Omega, \end{cases} \tag{39}$$

with $A^* = \frac{1}{2} \nabla_\theta \nabla_\theta \lambda_1(\theta_0)$.

Remark 3.9 *The one half factor in front of the initial data in the homogenized problem (39) is quite surprising. It arises because the initial velocity in (35) contains some contribution of u_ϵ^0. As already explained in the scalar case [3], there is an initial layer in time in (35) which is not taken into account by Theorem 3.8.*

Let us now assume that $\lambda_1(\theta_0) > 0$. We perform another time renormalization and we introduce a new unknown

$$\tilde{u}_\epsilon(t,x) = e^{-i\frac{\sqrt{\lambda_1(\theta_0)}t}{\epsilon^2}} u_\epsilon(t,x), \tag{40}$$

which satisfies

$$\begin{cases} \epsilon^2 \dfrac{\partial^2 \tilde{u}_\epsilon}{\partial t^2} + 2i\sqrt{\lambda_1(\theta_0)} \dfrac{\partial \tilde{u}_\epsilon}{\partial t} - \operatorname{div}\left(A\left(\dfrac{x}{\epsilon}\right)\nabla \tilde{u}_\epsilon\right) + \dfrac{c\left(\frac{x}{\epsilon}\right) - \lambda_1(\theta_0)}{\epsilon^2}\tilde{u}_\epsilon = 0 & \text{in } \Omega \times (0,T), \\ \tilde{u}_\epsilon = 0 & \text{on } \partial\Omega \times (0,T), \\ \tilde{u}_\epsilon(t=0,x) = u_\epsilon^0(x) & \text{in } \Omega, \\ \frac{\partial \tilde{u}_\epsilon}{\partial t}(t=0,x) = u_\epsilon^1(x) - i\frac{\sqrt{\lambda_1(\theta_0)}}{\epsilon^2} u_\epsilon^0(x) & \text{in } \Omega. \end{cases} \tag{41}$$

In this case we obtain a Schrödinger type homogenized equation.

Theorem 3.10 *Assume (9), $\lambda_1(\theta_0) > 0$ and that the initial data is*

$$u_\epsilon^0(x) = \psi_1\left(\frac{x}{\epsilon}, \theta_0\right) e^{2i\pi\frac{\theta_0 \cdot x}{\epsilon}} v^0(x) \in H_0^1(\Omega)^K, \tag{42}$$

with $v^0 \in L^2(\Omega)$, and that $\epsilon^2 u_\epsilon^1(x)$ is bounded in $L^2(\Omega)^K$ while $\epsilon^2 \psi_1\left(\frac{x}{\epsilon}, \theta_0\right) \cdot u_\epsilon^1(x)$ converges weakly to 0 in $L^2(\Omega)$. The solution of (35) can be written as

$$u_\epsilon(t,x) = e^{i\frac{\sqrt{\lambda_1(\theta_0)}t}{\epsilon^2}} e^{2i\pi\frac{\theta_0 \cdot x}{\epsilon}} v_\epsilon(t,x), \tag{43}$$

where v_ϵ two-scale converges to $\psi_1(y,\theta_0)v(t,x)$ and $v \in L^2\left((0,T); H_0^1(\Omega)\right)$ is the solution of the scalar homogenized problem

$$\begin{cases} 2i\sqrt{\lambda_1(\theta_0)}\dfrac{\partial v}{\partial t} - \operatorname{div}\left(A^* \nabla v\right) = 0 & \text{in } \Omega \times (0,T), \\ v = 0 & \text{on } \partial\Omega \times (0,T), \\ v(t=0,x) = \frac{1}{2} v^0(x) & \text{in } \Omega, \end{cases} \tag{44}$$

with $A^* = \frac{1}{2}\nabla_\theta \nabla_\theta \lambda_1(\theta_0)$.

Remark 3.11 *All the results in the hyperbolic case (Theorems 3.7, 3.8, and 3.10) hold true when we add a zero-order term of the type $d\left(x, \frac{x}{\epsilon}\right) u_\epsilon$, where $d(x,y)$ is a symmetric non-negative matrix with entries in $L^\infty\left(\Omega; C(\mathbb{T}^N)\right)$. This yields a zero-order term in the homogenized problem which is precisely $d^*(x) = \int_{\mathbb{T}^N} d(x,y)\psi_1(y) \cdot \overline{\psi}_1(y)\, dy$.*

4 Proofs in the parabolic case

Notation: for any function $\phi(x,y)$ defined on $\mathbb{R}^N \times \mathbb{T}^N$, we denote by ϕ^ϵ the function $\phi(x, \frac{x}{\epsilon})$.

Proof of Lemma 3.1. We multiply equation (19) by $\tilde{u}_\epsilon$ and we integrate by parts to obtain

$$\begin{aligned} &\frac{1}{2}\int_\Omega |\tilde{u}_\epsilon(t,x)|^2 dx - \frac{1}{2}\int_\Omega |u_\epsilon^0(x)|^2 dx + \int_0^t \int_\Omega d\left(x\frac{x}{\epsilon}\right)\tilde{u}_\epsilon \cdot \tilde{u}_\epsilon \, ds\, dx \\ &+ \int_0^t \int_\Omega \left(A\left(\frac{x}{\epsilon}\right)\nabla\tilde{u}_\epsilon \cdot \nabla\tilde{u}_\epsilon + \frac{c\left(\frac{x}{\epsilon}\right) - \lambda_1(\theta_0)}{\epsilon^2}\tilde{u}_\epsilon \cdot \tilde{u}_\epsilon \right) ds\, dx = 0. \end{aligned} \tag{45}$$

If we can check that the last integral in (45) is non negative, the lemma is proved by a standard Gronwall inequality. Extending $\tilde{u}_\epsilon$ by zero outside Ω and changing the variable as $y = \frac{x}{\epsilon}$, a sufficient condition is to prove that, for any $u \in H^1(\mathbb{R}^N)^K$,

$$\int_{\mathbb{R}^N} \left(A(y)\nabla u \cdot \nabla u + (c(y) - \lambda_1(\theta_0))\, u \cdot u\right) dy \geq 0.$$

Applying the Bloch decomposition of Lemma 2.4 to u yields

$$\int_{\mathbb{R}^N} \left(A(y)\nabla u \cdot \nabla u + (c(y) - \lambda_1(\theta_0))\, u \cdot u\right) dy = \sum_{k\geq 1} \int_{\mathbb{T}^N} |\alpha_k(\theta)|^2 \left(\lambda_k(\theta) - \lambda_1(\theta_0)\right) d\theta$$

which is non negative by assumption (9). □

Proof of Theorem 3.2. To simplify the exposition we forget the notation $\tilde{\cdot}$ for the solution $\tilde{u}_\epsilon$ of (19). Equivalently, we could have subtracted from $c(y)$ an adequate constant, so that $\lambda_1(\theta_0) = 0$ and $u_\epsilon = \tilde{u}_\epsilon$. Define a sequence w_ϵ by

$$w_\epsilon(t,x) = u_\epsilon(t,x) e^{-2i\pi\frac{\theta_0 \cdot x}{\epsilon}}.$$

By the a priori estimate of Lemma 3.1 we have

$$\|w_\epsilon\|_{L^\infty((0,T);L^2(\Omega)^K)} + \epsilon\|\nabla w_\epsilon\|_{L^2((0,T)\times\Omega)^K} \leq C,$$

and applying the compactness of two-scale convergence (see [2], [23]), up to a subsequence there exists a limit $w(t,x,y) \in L^2\left((0,T)\times\Omega; H^1(\mathbb{T}^N)^K\right)$ such that

$$w_\epsilon \overset{2s}{\rightharpoonup} w \quad \text{and} \quad \epsilon\nabla w_\epsilon \overset{2s}{\rightharpoonup} \nabla_y w$$

in the sense of two-scale convergence.

First step. We multiply (19) by the complex conjugate of $\epsilon^2\phi(t,x,\frac{x}{\epsilon})e^{2i\pi\frac{\theta_0\cdot x}{\epsilon}}$ where $\phi(t,x,y)$ is a smooth test function defined on $[0,T)\times\Omega\times\mathbb{T}^N$, with compact support in $[0,T)\times\Omega$, and with values in $\mathbb{C}^K$. Integrating by parts this yields

$$\begin{aligned}
&\epsilon^2\int_\Omega u_\epsilon^0\cdot\overline{\phi}^\epsilon e^{-2i\pi\frac{\theta_0\cdot x}{\epsilon}}dx-\epsilon^2\int_0^T\int_\Omega w_\epsilon\cdot\frac{\partial\overline{\phi}^\epsilon}{\partial t}dt\,dx\\
&+\int_0^T\int_\Omega A^\epsilon(\epsilon\nabla+2i\pi\theta_0)w_\epsilon\cdot(\epsilon\nabla-2i\pi\theta_0)\overline{\phi}^\epsilon\,dt\,dx\\
&+\int_0^T\int_\Omega(c^\epsilon-\lambda_1(\theta_0)+\epsilon^2d^\epsilon)w_\epsilon\cdot\overline{\phi}^\epsilon\,dt\,dx\qquad\qquad=0.
\end{aligned}$$

Passing to the two-scale limit yields the variational formulation of

$$-(\mathrm{div}_y+2i\pi\theta)\Big(A(y)(\nabla_y+2i\pi\theta)w\Big)+c(y)w=\lambda_1(\theta_0)w\quad\text{ in }\mathbb{T}^N.$$

By the simplicity of $\lambda_1(\theta_0)$, this implies that there exists a scalar function $v(t,x)\in L^2\left((0,T)\times\Omega\right)$ (possibly complex-valued) such that

$$w(t,x,y)=v(t,x)\psi_1(y,\theta_0). \tag{46}$$

Second step. We multiply (19) by the complex conjugate of

$$\Psi_\epsilon=e^{2i\pi\frac{\theta_0\cdot x}{\epsilon}}\left(\psi_1(\frac{x}{\epsilon},\theta_0)\phi(t,x)+\epsilon\sum_{k=1}^N\frac{\partial\phi}{\partial x_k}(t,x)\zeta_k(\frac{x}{\epsilon})\right) \tag{47}$$

where $\phi(t,x)$ is a smooth, compactly supported, test function defined from $[0,T)\times\Omega$ into $\mathbb{R}$, and $\zeta_k(y)$ is the solution of (14). After some algebra we

found that

$$\begin{aligned}\int_\Omega A^\epsilon \nabla u_\epsilon \cdot \nabla \overline{\Psi}_\epsilon dx &= \int_\Omega A^\epsilon (\nabla + 2i\pi\frac{\theta_0}{\epsilon})(\overline{\phi} w_\epsilon) \cdot (\nabla - 2i\pi\frac{\theta_0}{\epsilon})\overline{\psi}_1^\epsilon \\ &+\epsilon \int_\Omega A^\epsilon (\nabla + 2i\pi\frac{\theta_0}{\epsilon})(\frac{\partial\overline{\phi}}{\partial x_k} w_\epsilon) \cdot (\nabla - 2i\pi\frac{\theta_0}{\epsilon})\overline{\zeta}_k^\epsilon \\ &- \int_\Omega A^\epsilon e_k \frac{\partial\overline{\phi}}{\partial x_k} w_\epsilon \cdot (\nabla - 2i\pi\frac{\theta_0}{\epsilon})\overline{\psi}_1^\epsilon \\ &+ \int_\Omega A^\epsilon (\nabla + 2i\pi\frac{\theta_0}{\epsilon})(\frac{\partial\overline{\phi}}{\partial x_k} w_\epsilon) \cdot e_k \overline{\psi}_1^\epsilon \\ &- \int_\Omega A^\epsilon w_\epsilon \nabla \frac{\partial\overline{\phi}}{\partial x_k} \cdot e_k \overline{\psi}_1^\epsilon \\ &- \int_\Omega A^\epsilon w_\epsilon \nabla \frac{\partial\overline{\phi}}{\partial x_k} \cdot (\epsilon\nabla - 2i\pi\theta_0)\overline{\zeta}_k^\epsilon \\ &+ \int_\Omega A^\epsilon \overline{\zeta}_k^\epsilon (\epsilon\nabla + 2i\pi\theta_0) w_\epsilon \cdot \nabla \frac{\partial\overline{\phi}}{\partial x_k}\end{aligned} \tag{48}$$

Now, for any smooth compactly supported test function Φ from Ω into $\mathbb{C}^K$, we deduce from the definition of ψ_1 that

$$\int_\Omega A^\epsilon (\nabla + 2i\pi\frac{\theta_0}{\epsilon})\psi_1^\epsilon \cdot (\nabla - 2i\pi\frac{\theta_0}{\epsilon})\overline{\Phi} + \frac{1}{\epsilon^2}\int_\Omega (c^\epsilon - \lambda_1(\theta_0))\psi_1^\epsilon \cdot \overline{\Phi} = 0, \tag{49}$$

and from the definition of ζ_k

$$\begin{aligned}&\int_\Omega A^\epsilon (\nabla + 2i\pi\frac{\theta_0}{\epsilon})\zeta_k^\epsilon \cdot (\nabla - 2i\pi\frac{\theta_0}{\epsilon})\overline{\Phi} + \frac{1}{\epsilon^2}\int_\Omega (c^\epsilon - \lambda_1(\theta_0))\zeta_k^\epsilon \cdot \overline{\Phi} = \\ &\quad \epsilon^{-1}\int_\Omega A^\epsilon (\nabla + 2i\pi\frac{\theta_0}{\epsilon})\psi_1^\epsilon \cdot e_k\overline{\Phi} - \epsilon^{-1}\int_\Omega A^\epsilon e_k\psi_1^\epsilon \cdot (\nabla - 2i\pi\frac{\theta_0}{\epsilon})\overline{\Phi}.\end{aligned} \tag{50}$$

Combining (48) with the potential term, we easily check that the first line of its right hand side cancels out because of (49) with $\Phi = \phi\overline{w}_\epsilon$, and the next three lines cancel out because of (50) with $\Phi = \frac{\partial\phi}{\partial x_k}\overline{w}_\epsilon$. On the other hand, we can pass to the limit in the three last terms of (48). Finally, (19)

multiplied by $\overline{\Psi}_\epsilon$ yields after simplification

$$\begin{aligned}
&\int_\Omega u_\epsilon^0 \cdot \overline{\Psi}_\epsilon(t=0)dx - \int_0^T \int_\Omega w_\epsilon \cdot \left(\overline{\psi}_1^\epsilon \frac{\partial \overline{\phi}}{\partial t} + \epsilon \frac{\partial^2 \overline{\phi}}{\partial x_k \partial t} \overline{\zeta}_k^\epsilon \right) dt\, dx \\
&- \int_0^T \int_\Omega A^\epsilon w_\epsilon \nabla \frac{\partial \overline{\phi}}{\partial x_k} \cdot e_k \overline{\psi}_1^\epsilon dt\, dx \\
&- \int_0^T \int_\Omega A^\epsilon w_\epsilon \nabla \frac{\partial \overline{\phi}}{\partial x_k} \cdot (\epsilon \nabla - 2i\pi\theta_0) \overline{\zeta}_k^\epsilon dt\, dx \\
&+ \int_0^T \int_\Omega A^\epsilon \overline{\zeta}_k^\epsilon (\epsilon \nabla + 2i\pi\theta_0) w_\epsilon \cdot \nabla \frac{\partial \overline{\phi}}{\partial x_k} dt\, dx \\
&+ \int_0^T \int_\Omega d^\epsilon w_\epsilon \cdot \overline{\Psi}_\epsilon \, dt\, dx = 0.
\end{aligned} \tag{51}$$

Passing to the two-scale limit in each term of (51) gives

$$\begin{aligned}
&\int_\Omega \int_{\mathbb{T}^N} \psi_1 v^0 \cdot \overline{\psi}_1 \overline{\phi}(t=0) dx\, dy - \int_0^T \int_\Omega \int_{\mathbb{T}^N} \psi_1 v \cdot \overline{\psi}_1 \frac{\partial \overline{\phi}}{\partial t} dt\, dx\, dy \\
&- \int_0^T \int_\Omega \int_{\mathbb{T}^N} A \psi_1 v \nabla \frac{\partial \overline{\phi}}{\partial x_k} \cdot e_k \overline{\psi}_1 dt\, dx\, dy \\
&- \int_0^T \int_\Omega \int_{\mathbb{T}^N} A \psi_1 v \nabla \frac{\partial \overline{\phi}}{\partial x_k} \cdot (\nabla_y - 2i\pi\theta_0) \overline{\zeta}_k dt\, dx\, dy \\
&+ \int_0^T \int_\Omega \int_{\mathbb{T}^N} A \overline{\zeta}_k (\nabla_y + 2i\pi\theta_0) \psi_1 v \cdot \nabla \frac{\partial \overline{\phi}}{\partial x_k} dt\, dx\, dy \\
&+ \int_0^T \int_\Omega \int_{\mathbb{T}^N} d \psi_1 v \cdot \overline{\psi}_1 \overline{\phi}\, dt\, dx\, dy = 0.
\end{aligned} \tag{52}$$

Recalling the normalization $\int_{\mathbb{T}^N} |\psi_1|^2 dy = 1$, and introducing

$$\begin{aligned}
A^*_{jk} = \int_{\mathbb{T}^N} &\Big(A\psi_1 e_j \cdot e_k \overline{\psi}_1 + A\psi_1 e_k \cdot e_j \overline{\psi}_1 \\
&+ A\psi_1 e_j \cdot (\nabla_y - 2i\pi\theta_0) \overline{\zeta}_k + A\psi_1 e_k \cdot (\nabla_y - 2i\pi\theta_0) \overline{\zeta}_j \\
&- A\overline{\zeta}_k (\nabla_y + 2i\pi\theta_0) \psi_1 \cdot e_j - A\overline{\zeta}_j (\nabla_y + 2i\pi\theta_0) \psi_1 \cdot e_k \Big) dy,
\end{aligned} \tag{53}$$

and $d^*(x) = \int_{\mathbb{T}^N} d(x,y) \psi_1(y) \cdot \overline{\psi}_1(y)\, dy$, (52) is equivalent to

$$\int_\Omega v^0 \overline{\phi}(0) dx - \int_0^T \int_\Omega \left(v \frac{\partial \overline{\phi}}{\partial t} + A^* v \cdot \nabla \nabla \overline{\phi} - d^*(x) v \overline{\phi} \right) dt\, dx = 0$$

which is a very weak form of the homogenized equation (24). Note, however, that we can not recover the Dirichlet boundary condition from (52). To this end we shall use the compactness Lemma 4.2 below which was not required so far (and which holds true for functions depending on time, as claimed in Remark 4.3). Since, by the parabolic energy estimate, assumption (55) is satisfied, we deduce that there exists a bounded scalar sequence v_ϵ in $L^2\left((0,T);H^1(\mathbb{R}^N)\right)$ such that

$$u_\epsilon(t,x) = \psi_1\left(\frac{x}{\epsilon},\theta_0\right) e^{2i\pi\frac{\theta_0\cdot x}{\epsilon}} v_\epsilon(t,x) + r_\epsilon(t,x), \tag{54}$$

and $\lim_{\epsilon\to 0}\|r_\epsilon\|_{L^2((0,T)\times\omega)^K} = 0$ for any compact set $\omega\subset\mathbb{R}^N$. Up to a subsequence, v_ϵ converges weakly to a limit v in $L^2\left((0,T);H^1(\mathbb{R}^N)\right)$, which necessarily coincides with the two-scale limit obtained in (46). If the compact set ω lies outside Ω, i.e. $\omega\subset\left(\mathbb{R}^N\setminus\Omega\right)$, we deduce from (54) that

$$\psi_1\left(\frac{x}{\epsilon},\theta_0\right) v_\epsilon(t,x) = -r_\epsilon(t,x) \quad \text{in } \omega\times(0,T),$$

and since ψ_1 is normalized, we obtain

$$\|r_\epsilon\|^2_{L^2((0,T)\times\omega)^K} = \int_\omega |\psi_1\left(\frac{x}{\epsilon},\theta_0\right)|^2 |v_\epsilon(x)|^2 dx \to \int_\omega |v(x)|^2 dx \;=\; 0.$$

Therefore, we deduce that $v=0$ in any compact set ω outside from Ω. This implies that v belongs to $H^1_0(\Omega)$.

The compatibility condition of equation (15) for the second derivative of ψ_1 yields that the matrix A^*, defined by (53), is indeed equal to $\frac{1}{4\pi^2}\nabla_\theta\nabla_\theta\lambda_1(\theta_0)$, and thus is real, symmetric, positive definite by assumption (9). Therefore, the homogenized problem (24) is well posed. By uniqueness of the solution of the homogenized problem (24), we deduce that the entire sequence v_ϵ converges to v (which is a real-valued function). □

Remark 4.1 *As usual in periodic homogenization, the choice of the test function Ψ_ϵ, defined by (47), is dictated by the formal two-scale asymptotic expansion that can be obtained for the solution u_ϵ of (17). Indeed, if one admits that the ansatz of u_ϵ starts with the following two exponential terms (which is not obvious a priori !), then a simple and formal computation shows that*

$$u_\epsilon(t,x) \approx e^{-\frac{\lambda_1(\theta_0)t}{\epsilon^2}} e^{2i\pi\frac{\theta_0\cdot x}{\epsilon}} \left(\psi_1\left(\frac{x}{\epsilon},\theta_0\right) v(t,x) + \epsilon\sum_{k=1}^N \frac{\partial v}{\partial x_k}(t,x)\zeta_k(\frac{x}{\epsilon})\right),$$

where v is the homogenized solution of (24).

Lemma 4.2 *Let u_ϵ be a bounded sequence in $L^2(\mathbb{R}^N)^K$. Assume that there exists a finite constant C such that*

$$\int_{\mathbb{R}^N} \left(A\left(\frac{x}{\epsilon}\right) \nabla u_\epsilon \cdot \nabla u_\epsilon + \frac{c\left(\frac{x}{\epsilon}\right) - \lambda_1(\theta_0)}{\epsilon^2} u_\epsilon \cdot u_\epsilon \right) dx \leq C. \tag{55}$$

Then, under assumption (9),

$$u_\epsilon(x) = \psi_1\left(\frac{x}{\epsilon}, \theta_0\right) e^{2i\pi \frac{\theta_0 \cdot x}{\epsilon}} v_\epsilon(x) + r_\epsilon(x), \tag{56}$$

where v_ϵ is a bounded scalar sequence in $H^1(\mathbb{R}^N)$ and $\lim_{\epsilon \to 0} \|r_\epsilon\|_{L^2(\omega)^K} = 0$ for any compact set $\omega \subset \mathbb{R}^N$.

Remark 4.3 *If we consider functions depending on time, Lemma 4.2 is easily extended as follows. Assuming that u_ϵ is a bounded sequence in $L^2((0,T) \times \mathbb{R}^N)^K$ and that (55) holds true when integrated on the time interval $(0,T)$, the decomposition (56) is still valid with v_ϵ bounded in $L^2((0,T); H^1(\mathbb{R}^N))$ and r_ϵ converging strongly to 0 in $L^2((0,T); L^2_{loc}(\mathbb{R}^N))$.*

Remark 4.4 *If the sequence u_ϵ further vanishes outside an open set Ω, then we can obtain the representation (26) with v_ϵ uniformly bounded in $H^1_0(\Omega)$. Indeed, it is enough to project the function $v_\epsilon \in H^1(\mathbb{R}^N)$, given by Lemma 4.2, on $H^1_0(\Omega)$.*

Proof. Our proof is in the spirit of the previous works [18], [16]. Applying the rescaled Bloch decomposition (16) to $u_\epsilon(x)$ with $\eta = \frac{\theta - \theta_0}{\epsilon}$, we have

$$u_\epsilon(x) = \sum_{k \geq 1} \int_{\epsilon^{-1}\mathbb{T}^N} \alpha_k^\epsilon(\eta) \psi_k(\frac{x}{\epsilon}, \theta_0 + \epsilon\eta) e^{2i\pi\eta \cdot x} e^{2i\pi \frac{\theta_0 \cdot x}{\epsilon}} d\eta,$$

and

$$\begin{aligned} &\int_{\mathbb{R}^N} \left(A\left(\frac{x}{\epsilon}\right) \nabla u_\epsilon \cdot \nabla u_\epsilon + \frac{c\left(\frac{x}{\epsilon}\right) - \lambda_1(\theta_0)}{\epsilon^2} u_\epsilon \cdot u_\epsilon \right) dx \\ &= \epsilon^{-2} \sum_{k \geq 1} \int_{\epsilon^{-1}\mathbb{T}^N} |\alpha_k^\epsilon(\eta)|^2 \Big(\lambda_k(\theta_0 + \epsilon\eta) - \lambda_1(\theta_0) \Big) d\eta. \end{aligned}$$

Since $\lambda_k(\theta) - \lambda_1(\theta_0) \geq 0$ and, for $k \geq 2$, $\lambda_k(\theta) - \lambda_1(\theta_0) \geq C > 0$, we deduce from the bound (55) that

$$\sum_{k \geq 2} \int_{\epsilon^{-1}\mathbb{T}^N} |\alpha_k^\epsilon(\eta)|^2 d\eta \leq C\epsilon^2.$$

For $k=1$, by assumption (9) there exists $C>0$ such that

$$\lambda_1(\theta)-\lambda_1(\theta_0)\geq C|\theta-\theta_0|^2 \quad \forall \theta\in\mathbb{T}^N,$$

and thus (55) implies

$$\int_{\epsilon^{-1}\mathbb{T}^N}|\eta|^2|\alpha_1^\epsilon(\eta)|^2d\eta\leq C.$$

Extending $\alpha_1^\epsilon(\eta)$ by zero outside $\epsilon^{-1}\mathbb{T}^N$, and using the inverse Fourier transform, we deduce that the scalar sequence v_ϵ, defined by

$$v_\epsilon(x)=\int_{\mathbb{R}^N}\alpha_1^\epsilon(\eta)e^{2i\pi\eta\cdot x}d\eta,$$

is bounded in $H^1(\mathbb{R}^N)$.

Introducing a parameter $0<q<1$ (to be chosen later) we define a cut-off of v_ϵ by

$$\tilde{v}_\epsilon=\int_{|\eta|<\epsilon^{-q}}\alpha_1^\epsilon(\eta)e^{2i\pi\eta\cdot x}d\eta.$$

The difference between v_ϵ and $\tilde{v}_\epsilon$ is small since

$$\|\tilde{v}_\epsilon-v_\epsilon\|^2_{L^2(\mathbb{R}^N)}=\int_{|\eta|>\epsilon^{-q}}|\alpha_1^\epsilon(\eta)|^2d\eta\leq\epsilon^{2q}\int_{\mathbb{R}^N}|\eta|^2|\alpha_1^\epsilon(\eta)|^2d\eta\leq C\epsilon^{2q}.$$

Similarly we have

$$\int_{\epsilon^{-1}\mathbb{T}^N}\alpha_1^\epsilon(\eta)\psi_1(\frac{x}{\epsilon},\theta_0+\epsilon\eta)e^{2i\pi\eta\cdot x}e^{2i\pi\frac{\theta_0\cdot x}{\epsilon}}d\eta=\int_{|\eta|<\epsilon^{-q}}\alpha_1^\epsilon(\eta)\psi_1(\frac{x}{\epsilon},\theta_0+\epsilon\eta)e^{2i\pi\eta\cdot x}e^{2i\pi\frac{\theta_0\cdot x}{\epsilon}}d\eta+t_\epsilon(x),$$

where t_ϵ is small, i.e.

$$\|t_\epsilon\|^2_{L^2(\mathbb{R}^N)}=\int_{\eta\in\epsilon^{-1}\mathbb{T}^N,\ |\eta|>\epsilon^{-q}}|\alpha_1^\epsilon(\eta)|^2d\eta\leq\epsilon^{2q}\int_{\epsilon^{-1}\mathbb{T}^N}|\eta|^2|\alpha_1^\epsilon(\eta)|^2d\eta\leq C\epsilon^{2q}.$$

By the analycity of the first eigencouple of (8), there exists a periodic function $\chi\in L^2(\mathbb{T}^N)$ such that

$$|\psi_1(y,\theta)-\psi_1(y,\theta_0)|\leq|\theta-\theta_0|\chi(y)\quad\forall y\in\mathbb{T}^N,\theta\in\mathbb{T}^N.$$

Therefore, we have

$$\int_{|\eta|<\epsilon^{-q}}\alpha_1^\epsilon(\eta)\psi_1(\frac{x}{\epsilon},\theta_0+\epsilon\eta)e^{2i\pi\eta\cdot x}e^{2i\pi\frac{\theta_0\cdot x}{\epsilon}}d\eta=\psi_1(\frac{x}{\epsilon},\theta_0)e^{2i\pi\frac{\theta_0\cdot x}{\epsilon}}\tilde{v}_\epsilon(x)+s_\epsilon(x)$$

where s_ϵ is small, i.e.

$$\begin{aligned}|s_\epsilon(x)| &\leq \chi(\frac{x}{\epsilon}) \int_{|\eta|<\epsilon^{-q}} \epsilon|\eta||\alpha_1^\epsilon(\eta)|\, d\eta \\ &\leq \epsilon\chi(\frac{x}{\epsilon}) \left(\int_{|\eta|<\epsilon^{-q}} |\eta|^2|\alpha_1^\epsilon(\eta)|^2 d\eta\right)^{1/2} \left(\int_{|\eta|<\epsilon^{-q}} d\eta\right)^{1/2} \\ &\leq C\epsilon^{1-\frac{Nq}{2}}\chi(\frac{x}{\epsilon}).\end{aligned}$$

Thus, we obtain that, for any compact set $\omega \subset \mathbb{R}^N$,

$$\|s_\epsilon\|^2_{L^2(\omega)^K} \leq C|\omega|\epsilon^{1-\frac{Nq}{2}}.$$

(We can not obtain a uniform estimate on $\mathbb{R}^N$ since s_ϵ is not defined as a Bloch decomposition.) Collecting all the intermediate steps we deduce

$$u_\epsilon(x) = \psi_1(\frac{x}{\epsilon}, \theta_0)e^{2i\pi\frac{\theta_0\cdot x}{\epsilon}}\tilde{v}_\epsilon(x) + r_\epsilon(x)$$

and $\|r_\epsilon\|_{L^2(\omega)^K} \leq C|\omega|\epsilon^{\frac{2}{N+2}}$ with the optimal value of q equal to $2/(N+2)$. □

Remark 4.5 *If we remove from assumption (9) the positive definite character of the Hessian matrix $\nabla_\theta\nabla_\theta\lambda_1(\theta_0)$, we can still obtained an homogenization result, weaker than Theorem 3.2. Indeed, the same proof shows that w_ϵ two-scales converges, up to a subsequence, to $\psi_1(y,\theta_0)v(t,x)$ where v is a solution of the homogenized equation (24) with a possibly degenerate matrix A^* (which is nevertheless always non-negative because θ_0 is a minimum point). However, Lemma 4.2 holds true only if $\nabla_\theta\nabla_\theta\lambda_1(\theta_0)$ is positive definite. Thus, we can not recover the Dirichlet boundary condition, neither can we obtain the uniqueness of the homogenized solution and the convergence of the entire sequence w_ϵ.*

Remark 4.6 *If we remove from assumption (9) the fact that the minimum point θ_0 of $\lambda_1(\theta)$ is unique, then we can also prove a weaker version of Theorem 3.2. For each minimum and associated Hessian matrix $\nabla_\theta\nabla_\theta\lambda_1$, we can extract a subsequence such that w_ϵ two-scales converges $\psi_1(y,\theta_0)v(t,x)$ where v is a solution of the homogenized equation (24). However, since Lemma 4.2 does not hold true in this case, we can not recover the Dirichlet boundary condition. Nevertheless, if $\Omega = \mathbb{R}^N$ and $\nabla_\theta\nabla_\theta\lambda_1$ is positive definite,*

we do not need any boundary condition to obtain the unique solvability of the homogenized equation. Thus, in such a case, the entire sequence w_ϵ is converging. Recall that $w_\epsilon = e^{\frac{\lambda_1(\theta_0)t}{\epsilon^2}} e^{-2i\pi\frac{\theta_0\cdot x}{\epsilon}} u_\epsilon$, so that for different minima we have different values of θ_0, thus different sequences w_ϵ, and eventually different homogenized problems. If the initial condition is a superposition of well-prepared initial data for each minimum point θ_0, then, by linearity, we can decompose the solution in a superposition of elementary solutions, each of them converging to its own homogenized limit depending on θ_0.

5 Proofs for the spectral problem

This section is devoted to the proof of Theorem 3.6. For simplicity reasons, we first prove the analogue of this result in the whole space, $\Omega = \mathbb{R}^N$, with, on top of (9), the additional assumption

$$\lim_{|x|\to+\infty} \sum_{\alpha,\beta=1}^{K} d_{\alpha\beta}(x,y)\eta_\alpha\eta_\beta = +\infty \text{ uniformly in } y \in \mathbb{T}^N, \eta \in \{|\eta| = 1\}. \quad (57)$$

Under this assumption, it is well-known that the following spectral problem

$$-\mathrm{div}\left(A\left(\frac{x}{\epsilon}\right)\nabla u_\epsilon\right) + \epsilon^{-2} c\left(\frac{x}{\epsilon}\right) u_\epsilon + d\left(x, \frac{x}{\epsilon}\right) u_\epsilon = \lambda_\epsilon u_\epsilon \quad \text{in } \mathbb{R}^N \quad (58)$$

has a discrete spectrum in $L^2(\mathbb{R}^N)^K$, $\lambda_1^\epsilon \le \lambda_2^\epsilon \le \ldots \le \lambda_n^\epsilon \ldots \to +\infty$, with corresponding orthonormal eigenfunctions denoted by $u_1^\epsilon(x)$, $u_2^\epsilon(x)$, ... Similarly, since $\lim_{|x|\to+\infty} d^*(x) = +\infty$, the homogenized problem (27) has a discrete spectrum, $\mu_1, \mu_2, \ldots, \mu_n, \ldots \to +\infty$, with corresponding orthonormal eigenfunctions denoted by $v_1(x), v_2(x), \ldots$.

Lemma 5.1 *There exists a constant $C > 0$, which does not depend on ϵ, such that*

$$\frac{\lambda_1(\theta_0)}{\epsilon^2} + C \le \lambda_1^\epsilon \le \frac{\lambda_1(\theta_0)}{\epsilon^2} + \mu_1 + o(1), \quad (59)$$

where $o(1)$ vanishes as $\epsilon \to 0$.

Proof. We assume that v_1 is smooth enough, which is not a restriction since the general case can be reduced to this one by means of approximation. We write down the variational formulation

$$\lambda_1^\epsilon = \min_{\|u\|_{L^2(\mathbb{R}^N)^K}=1} \int_{\mathbb{R}^N} \left(A^\epsilon \nabla u \cdot \nabla \overline{u} + \left(\epsilon^{-2} c^\epsilon + d^\epsilon\right) u \cdot \overline{u}\right) dx \quad (60)$$

and substitute a test function of the form

$$U^\epsilon = \gamma_\epsilon e^{2i\pi\frac{\theta_0\cdot x}{\epsilon}}\left(\psi_1(\frac{x}{\epsilon},\theta_0)v_1(x)+\epsilon\sum_{k=1}^N\frac{\partial v_1}{\partial x_k}(x)\zeta_k(\frac{x}{\epsilon})\right), \tag{61}$$

where ζ_k is the solution of (14) and γ_ϵ is a normalization constant chosen in such a way that $\|U^\epsilon\|_{L^2(\mathbb{R}^N)^K}=1$. Since ψ_1 and ζ_k are periodic functions, and due to the assumptions on v_1, we have $\lim_{\epsilon\to 0}\gamma_\epsilon = 1$. In view of (10) and (14), after simple rearrangements we obtain

$$\begin{aligned}
\lambda_1^\epsilon \le \frac{\lambda_1(\theta_0)}{\epsilon^2}+o(1)+\gamma_\epsilon^2\int_{\mathbb{R}^N}A^\epsilon_{\alpha\beta,kl}\psi^\epsilon_{1,\alpha}\bar\psi^\epsilon_{1,\beta}\frac{\partial v_1}{\partial x_k}\frac{\partial v_1}{\partial x_l}dx\\
+\gamma_\epsilon^2\int_{\mathbb{R}^N}\Big\{\bar\psi^\epsilon_{1,\alpha}A^\epsilon_{\alpha\beta,ml}\left(\frac{\partial}{\partial y_m}+2i\pi\theta_{0,m}\right)\zeta^\epsilon_{k,\beta}\frac{\partial v_1}{\partial x_l}\frac{\partial v_1}{\partial x_k}\\
+\psi^\epsilon_{1,\alpha}\left(\frac{\partial}{\partial y_k}-2i\pi\theta_{0,k}\right)\left(A^\epsilon_{\alpha\beta,km}\bar\zeta^\epsilon_{l,\beta}\right)\frac{\partial v_1}{\partial x_m}\frac{\partial v_1}{\partial x_l}\Big\}dx\\
+\gamma_\epsilon^2\int_{\mathbb{R}^N}\bar\psi^\epsilon_{1,\alpha}\psi^\epsilon_{1,\beta}d^\epsilon_{\alpha\beta}|v_1|^2dx+\epsilon^2\gamma_\epsilon^2\int_{\mathbb{R}^N}d^\epsilon(\zeta^\epsilon\nabla v_1)\cdot(\bar\zeta^\epsilon\nabla v_1)dx\\
+2\epsilon\gamma_\epsilon^2\mathcal{R}\left(\int_{\mathbb{R}^N}\left(\bar\psi^\epsilon_1\zeta^\epsilon A^\epsilon\nabla\nabla v_1 v_1+d^\epsilon(v_1\bar\psi^\epsilon_1)\cdot(\zeta^\epsilon\nabla v_1)\right)dx\right).
\end{aligned}$$

¿From the definitions of A^* and d^*, we deduce the upper bound in (59). On the other hand, by using Lemma 2.4 we have

$$\min_{\|u\|_{L^2(\mathbb{R}^N)^K}=1}\int_{\mathbb{R}^N}\left(A^\epsilon\nabla u\cdot\nabla\overline{u}+\left(\epsilon^{-2}c^\epsilon+d^\epsilon\right)u\cdot\overline{u}\right)dx\ge \tag{62}$$

$$\frac{\lambda_1(\theta_0)}{\epsilon^2}+\inf_{x\in\mathbb{R}^N,y\in\mathbb{T}^N,|\eta|=1}d(x,y)\eta\cdot\eta$$

which yields the desired lower bound. □

Lemma 5.2 *There exists a scalar sequence v_ϵ which is relatively compact in $L^2(\mathbb{R}^N)$ and such that*

$$u_1^\epsilon(x)=v_\epsilon(x)\psi_1(\frac{x}{\epsilon},\theta_0)e^{2i\pi\frac{\theta_0\cdot x}{\epsilon}}+r_\epsilon(x)$$

where

$$\lim_{\epsilon\to 0}\|r_\epsilon\|_{L^2(\mathbb{R}^N)^K}=0, \qquad \|v_\epsilon\|_{H^1(\mathbb{R}^N)}\le C.$$

Remark 5.3 *As a consequence of Lemma 5.2 v_ϵ is almost normalized, i.e.* $\|v_\epsilon\|_{L^2(\mathbb{R}^N)}=1+o(1)$.

Proof. ¿From Lemma 5.1 we deduce

$$\frac{\lambda_1(\theta_0)}{\epsilon^2}+\int_{\mathbb{R}^N} d^\epsilon u_1^\epsilon\cdot\overline{u}_1^\epsilon\,dx\le\lambda_1^\epsilon\le\frac{\lambda_1(\theta_0)}{\epsilon^2}+\mu_1+o(1),$$

which implies that

$$\int_{\mathbb{R}^N} d^\epsilon u_1^\epsilon\cdot\overline{u}_1^\epsilon\,dx\le C. \tag{63}$$

Then, the first part of Lemma 5.2 is a consequence of Lemma 4.2 since

$$\int_{\mathbb{R}^N}\left(A^\epsilon\nabla u_1^\epsilon\cdot\nabla\overline{u}_1^\epsilon+\epsilon^{-2}\left(c^\epsilon-\lambda_1(\theta_0)\right)u_1^\epsilon\cdot\overline{u}_1^\epsilon\right)dx=\lambda_1^\epsilon-\frac{\lambda_1(\theta_0)}{\epsilon^2}-\int_{\mathbb{R}^N} d^\epsilon u_1^\epsilon\cdot\overline{u}_1^\epsilon\,dx\le C.$$

To obtain the relative compactness of v_ϵ in $L^2(\mathbb{R}^N)$ we deduce from (63) and the growth condition on $d^\epsilon(x)$ at infinity, that for each $\delta>0$ there is $R=R(\delta)$ such that

$$\|u_1^\epsilon\|_{L^2(\{x\,:\,|x|\ge R\})^K}<\delta. \tag{64}$$

Since v_ϵ is bounded in $H^1(\mathbb{R}^N)$, we can replace $(\psi_1)^2$ by its positive average in (64) and thus obtain

$$\|v_\epsilon\|_{L^2(\{x\,:\,|x|\ge R\})}<\delta,$$

which implies the relative compactness. □

Proof of Theorem 3.6 for $\Omega=\mathbb{R}^N$.

We focus on the first eigenfunction, $k=1$. For $k>1$ a similar proof holds true.

By Lemma 5.2 the family v_ϵ is relatively compact in $L^2(\mathbb{R}^N)$. Moreover, any limit point v^0 of a converging subsequence, satisfies the relation $\|v^0\|_{L^2(\mathbb{R}^N)}=1$. By Lemma 5.1 we can also extract a subsequence such that $\lambda_1^\epsilon-\frac{\lambda_1(\theta_0)}{\epsilon^2}$ converges to a limit $\bar\mu$. According to (59)

$$C\le\bar\mu\le\mu_1. \tag{65}$$

The proof is now very similar to that of Theorem 3.2 (see Section 4). Up to another subsequence, $e^{-2\pi i x\cdot\theta_0/\epsilon}u_1^\epsilon(x)$ two-scale converges to a limit $u_1^0(x,y)$ and $\epsilon\nabla\left(e^{-2\pi i x\cdot\theta_0/\epsilon}u_1^\epsilon\right)$ two-scale converges to $\nabla_y u_1^0(x,y)$. As in the first step of the proof of Theorem 3.2, one can easily show that

$$u_1^0(x,y) = v^0(x)\psi_1(y,\theta_0),$$

where v^0 is a limit point of v_ϵ. To find the equation satisfied by v^0, we proceed as in the second step of the proof of Theorem 3.2. We multiply (58) by the test function

$$\Psi_\epsilon(x) = e^{2i\pi\frac{\theta_0\cdot x}{\epsilon}}\left(\psi_1(\frac{x}{\epsilon},\theta_0)\phi(x) + \epsilon\sum_{k=1}^N \frac{\partial\phi}{\partial x_k}(x)\zeta_k(\frac{x}{\epsilon})\right),$$

where ϕ is smooth with compact support. This yields

$$\int_{\mathbb{R}^N} A^\epsilon(x)\nabla u_1^\epsilon(x)\nabla\overline{\Psi}_\epsilon(x)dx + \int_{\mathbb{R}^N}\frac{c^\epsilon(x)-\lambda_1(\theta_0)}{\epsilon^2}u_1^\epsilon(x)\cdot\overline{\Psi}_\epsilon(x)dx +$$

$$+\int_{\mathbb{R}^N} d^\epsilon(x)u_1^\epsilon(x)\cdot\overline{\Psi}_\epsilon(x) = \frac{\lambda_1^\epsilon-\lambda_1(\theta_0)}{\epsilon^2}\int_{\mathbb{R}^N} u_1^\epsilon(x)\cdot\overline{\Psi}_\epsilon(x).$$

As before, using (8) and (14), we can pass to the two scale limit to obtain

$$\int_{\mathbb{R}^N}\left(A^*v^0\cdot\nabla\nabla\overline{\phi} + d^*(x)v^0\overline{\phi}\right)dx = \bar{\mu}\int_{\mathbb{R}^N} v^0\varphi\,dx$$

which is a weak variational formulation of

$$-A^*\cdot\nabla\nabla v^0 + d^*v^0 = \bar{\mu}v^0 \quad \text{in} \quad \mathbb{R}^N. \tag{66}$$

Since $v^0\neq 0$ and $\bar{\mu}\leq\mu_1$, we necessarily have

$$\bar{\mu} = \mu_1,$$

and v^0 is an eigenfunction of (27) associated with μ_1. If μ_1 is simple, up to a convenient renormalization, the entire sequence u_1^ϵ is converging (and not merely a subsequence). □

Proof of Theorem 3.6 for a bounded open set Ω.

We merely outline the differences with the case $\Omega = \mathbb{R}^N$. In the proof of Lemma 5.1, in order to get an upper bound for λ_1^ϵ, we can not use the test function (61) because it does not satisfy the Dirichlet boundary condition. Therefore we replace v_1 by a convenient approximation. For each small $\delta > 0$, we introduce a smooth and compactly supported in Ω function w^δ, such that $\|w^\delta\|_{L^2(\Omega)} = 1$ and

$$\int_\Omega \left(A^* \nabla w^\delta \cdot \nabla \bar{w}^\delta + d^*(x) |w^\delta|^2 \right) dx < \mu_1 + \delta.$$

Substituting in the Rayleigh quotient defining λ_1^ϵ a test function of the form

$$U_\delta^\epsilon = \gamma_\epsilon e^{2i\pi \frac{\theta_0 \cdot x}{\epsilon}} \left(\psi_1(\frac{x}{\epsilon}, \theta_0) w^\delta(x) + \epsilon \sum_{k=1}^N \frac{\partial w^\delta}{\partial x_k}(x) \zeta_k(\frac{x}{\epsilon}) \right),$$

in the same manner we get the estimate

$$\lambda_1^\epsilon \leq \frac{\lambda_1(\theta_0)}{\epsilon^2} + \mu_1 + \delta + o(1), \tag{67}$$

where $o(1)$ vanishes as $\epsilon \to 0$. Since δ is an arbitrary positive number, this yields the required upper bound. The lower bound is obtained as before, extending first u_1^ϵ to the whole space $\mathbb{R}^N$ by setting $u_1^\epsilon(x) = 0$ for $x \in \mathbb{R}^N \setminus \Omega$, and using formula (16).

Lemma 5.2 is unchanged, equation (66) is obtained as before, and the Dirichlet boundary condition for the limit v^0 is recovered as in the parabolic case (see the end of the proof of Theorem 3.2). □

6 Proofs in the hyperbolic case

We begin with proof of Theorem 3.7 when $\lambda_1(\theta_0) = 0$. Actually, as soon as uniform a priori estimates are obtained for the solution of equation (28), the proof of convergence is completely similar to that of Theorem 3.2 in the parabolic case. Therefore, for the sake of brevity, we content ourselves in establishing those a priori estimates.

Lemma 6.1 *Under the assumptions of Theorem 3.7 the solution u_ϵ of (28) satisfies*

$$\|u_\epsilon\|_{L^\infty((0,T);L^2(\Omega)^K)} + \epsilon \|\nabla u_\epsilon\|_{L^2((0,T)\times\Omega)^{N\times K}} + \|\frac{\partial u_\epsilon}{\partial t}\|_{L^\infty((0,T);L^2(\Omega)^K)} \leq C, \tag{68}$$

where $C > 0$ is a constant which does not depend on ϵ. Furthermore, there exists a scalar sequence v_ϵ, uniformly bounded in $L^2((0,T);H^1(\Omega))$, such that

$$u_\epsilon(t,x) = \psi_1\left(\frac{x}{\epsilon},\theta_0\right) e^{2i\pi\frac{\theta_0\cdot x}{\epsilon}} v_\epsilon(t,x) + r_\epsilon(t,x), \tag{69}$$

where r_ϵ is a remainder term such that

$$\lim_{\epsilon\to 0} \|r_\epsilon\|_{L^2((0,T)\times\omega)^K} = 0 \text{ for any compact set } \omega \subset \mathbb{R}^N. \tag{70}$$

Proof. We multiply (28) by $\frac{\partial u_\epsilon}{\partial t}$ to obtain the usual energy estimate

$$E_\epsilon(t) = E_\epsilon(0) \text{ with } E_\epsilon(t) = \frac{1}{2}\int_\Omega \left(\left|\frac{\partial u_\epsilon}{\partial t}\right|^2 + A^\epsilon \nabla u_\epsilon\cdot\nabla u_\epsilon + \frac{c^\epsilon}{\epsilon^2} u_\epsilon\cdot u_\epsilon\right) dx. \tag{71}$$

Since $\lambda_1(\theta_0) = 0$, by using (8), a classical computation shows that

$$E_\epsilon(0) = \frac{1}{2}\int_\Omega \left(\left|u_\epsilon^1\right|^2 + A^\epsilon(\psi_\epsilon^1\otimes\nabla v^0)\cdot(\psi_\epsilon^1\otimes\nabla v^0)\right) dx,$$

which is uniformly bounded by assumption. Then, the Bloch wave analysis of Lemma 3.1 yields

$$\int_\Omega \left(A^\epsilon\nabla u_\epsilon\cdot\nabla u_\epsilon + \frac{c^\epsilon}{\epsilon^2}u_\epsilon\cdot u_\epsilon\right) dx \geq 0.$$

Therefore, we deduce (68) from (71). To obtain (69) and (70) we use Lemma 4.2 since (71) implies that assumption (55) is satisfied. □

We now turn to the proof of Theorem 3.8 when $\lambda_1(\theta_0) < 0$. Once again the proof of convergence is very similar to that of Theorem 3.2 as soon as uniform a priori estimates are established (see [3] in the scalar case if necessary). Therefore, we restrict ourselves to obtaining a priori estimates for the rescaled hyperbolic system (37).

Lemma 6.2 *Under the assumptions of Theorem 3.8 the solution $\tilde{u}_\epsilon$ of (37) satisfies*

$$\|\tilde{u}_\epsilon\|_{L^\infty((0,T);L^2(\Omega)^K)} + \epsilon\|\nabla\tilde{u}_\epsilon\|_{L^2((0,T)\times\Omega)^{N\times K}} + \epsilon\|\frac{\partial\tilde{u}_\epsilon}{\partial t}\|_{L^2((0,T)\times\Omega)^K} \leq C, \tag{72}$$

where $C > 0$ is a constant which does not depend on ϵ. Furthermore, there exists a scalar sequence v_ϵ, uniformly bounded in $L^2\left((0,T);H^1(\Omega)\right)$, such that

$$\tilde{u}_\epsilon(t,x) = \psi_1\left(\frac{x}{\epsilon},\theta_0\right) e^{2i\pi\frac{\theta_0\cdot x}{\epsilon}} v_\epsilon(t,x) + r_\epsilon(t,x), \tag{73}$$

where r_ϵ is a remainder term such that

$$\lim_{\epsilon\to 0} \|r_\epsilon\|_{L^2((0,T)\times\omega)^K} = 0 \text{ for any compact set } \omega \subset \mathbb{R}^N. \tag{74}$$

Proof. In a first step we multiply (35) by $\frac{\partial\tilde{u}_\epsilon}{\partial t}$ to obtain the usual energy estimate

$$E_\epsilon(T) + 2\sqrt{-\lambda_1(\theta_0)}\int_0^T\int_\Omega \left|\frac{\partial\tilde{u}_\epsilon}{\partial t}\right|^2 dx\,dt = E_\epsilon(0) \tag{75}$$

with

$$E_\epsilon(t) = \frac{1}{2}\int_\Omega \left(\epsilon^2\left|\frac{\partial\tilde{u}_\epsilon}{\partial t}\right|^2 + A^\epsilon\nabla\tilde{u}_\epsilon\cdot\nabla\tilde{u}_\epsilon + \frac{c^\epsilon-\lambda_1(\theta_0)}{\epsilon^2}\tilde{u}_\epsilon\cdot\tilde{u}_\epsilon\right) dx.$$

As in the proof of Lemma 6.1, using (8) yields

$$\int_\Omega \left(A^\epsilon\nabla u_\epsilon^0\cdot\nabla u_\epsilon^0 + \frac{c^\epsilon-\lambda_1(\theta_0)}{\epsilon^2}u_\epsilon^0\cdot u_\epsilon^0\right) dx = \int_\Omega A^\epsilon(\psi_\epsilon^1\otimes\nabla v^0)\cdot(\psi_\epsilon^1\otimes\nabla v^0)\,dx,$$

which is however not sufficient to show that $E_\epsilon(0)$ is uniformly bounded. Indeed we have

$$\frac{\partial\tilde{u}_\epsilon}{\partial t}(0) = u_\epsilon^1 - \frac{\sqrt{-\lambda_1(\theta_0)}}{\epsilon^2}u_\epsilon^0$$

which merely implies

$$E_\epsilon(0) \le C\epsilon^{-2}.$$

Nevertheless, from the Bloch wave analysis of Lemma 3.1 we deduce

$$\int_\Omega \left(A^\epsilon\nabla\tilde{u}_\epsilon\cdot\nabla\tilde{u}_\epsilon + \frac{c^\epsilon-\lambda_1(\theta_0)}{\epsilon^2}\tilde{u}_\epsilon\cdot\tilde{u}_\epsilon\right) dx \ge 0,$$

which, combined with (75), yields

$$\epsilon^2\|\frac{\partial\tilde{u}_\epsilon}{\partial t}\|_{L^\infty((0,T);L^2(\Omega)^K)} + \epsilon\sqrt{-\lambda_1(\theta_0)}\|\frac{\partial\tilde{u}_\epsilon}{\partial t}\|_{L^2((0,T)\times\Omega)^K} \le C. \tag{76}$$

In a second step we multiply (35) by $\tilde{u}_\epsilon$ to obtain a better energy estimate

$$\sqrt{-\lambda_1(\theta_0)}\int_\Omega |\tilde{u}_\epsilon(T)|^2\,dx + \int_0^T\int_\Omega \left(A^\epsilon\nabla\tilde{u}_\epsilon\cdot\nabla\tilde{u}_\epsilon + \frac{c^\epsilon-\lambda_1(\theta_0)}{\epsilon^2}\tilde{u}_\epsilon\cdot\tilde{u}_\epsilon\right)dx\,dt =$$
$$\sqrt{-\lambda_1(\theta_0)}\int_\Omega |\tilde{u}_\epsilon(0)|^2\,dx + \epsilon^2\int_0^T\int_\Omega \left|\frac{\partial\tilde{u}_\epsilon}{\partial t}\right|^2 dx\,dt$$
$$+\epsilon^2\int_\Omega \tilde{u}_\epsilon(0)\frac{\partial\tilde{u}_\epsilon}{\partial t}(0)\,dx - \epsilon^2\int_\Omega \tilde{u}_\epsilon(T)\frac{\partial\tilde{u}_\epsilon}{\partial t}(T)\,dx. \tag{77}$$

Using (76) we deduce from (77)

$$\sqrt{-\lambda_1(\theta_0)}\|\tilde{u}_\epsilon(T)\|^2_{L^2(\Omega)^K} \le C\left(1+\|\tilde{u}_\epsilon(T)\|_{L^2(\Omega)^K}\right),$$

which implies that $\tilde{u}_\epsilon$ is bounded in $L^\infty\left((0,T);L^2(\Omega)^K\right)$. Using this information in (77) shows that assumption (55) is satisfied: thus, Lemma 4.2 can be applied to obtain (73) and (74). □

Finally we arrive at the proof of Theorem 3.10 when $\lambda_1(\theta_0) > 0$ and again we simply address the question of uniform a priori estimates for (41) (the proof of convergence is an adaptation of Theorem 3.2 and of the arguments of [3] in the scalar case).

Lemma 6.3 *Under the assumptions of Theorem 3.10 the solution $\tilde{u}_\epsilon$ of (41) satisfies*

$$\|\tilde{u}_\epsilon\|_{L^\infty((0,T);L^2(\Omega)^K)} + \epsilon\|\nabla\tilde{u}_\epsilon\|_{L^2((0,T)\times\Omega)^{N\times K}} + \epsilon\left\|\frac{\partial\tilde{u}_\epsilon}{\partial t}\right\|_{L^2((0,T)\times\Omega)^K} \le C, \tag{78}$$

where $C > 0$ is a constant which does not depend on ϵ.

Remark 6.4 *The a priori estimates of Lemma 6.3 are weaker than the previous ones and in particular do not allow us to recover the homogenized Dirichlet boundary condition. As in the scalar case [3], in order to obtain the homogenized boundary condition the trick is to study the homogenization of a time integral of (41) which has less oscillating initial data. Indeed, defining $w_\epsilon(t,x) = \int_0^t \tilde{u}_\epsilon(s,x)\,ds + \chi_\epsilon(x)$ with a suitable choice of χ_ϵ (so that w_ϵ satisfies the same p.d.e. than (41) without source term), one can obtain better a priori estimates for w_ϵ than for $\tilde{u}_\epsilon$.*

Proof. In a first step we multiply (41) by $\frac{\partial\overline{\tilde{u}_\epsilon}}{\partial t}$ and we take the real part to obtain the usual energy estimate

$$E_\epsilon(t) = E_\epsilon(0) \tag{79}$$

with $E_\epsilon(t) = \frac{1}{2}\int_\Omega \left(\epsilon^2 \left|\frac{\partial\tilde{u}_\epsilon}{\partial t}\right|^2 + A^\epsilon \nabla\tilde{u}_\epsilon \cdot \nabla\overline{\tilde{u}_\epsilon} + \frac{c^\epsilon - \lambda_1(\theta_0)}{\epsilon^2}\tilde{u}_\epsilon \cdot \overline{\tilde{u}_\epsilon}\right) dx$. As in the proof of Lemma 6.2, the assumptions merely imply

$$E_\epsilon(0) \leq C\epsilon^{-2}.$$

Nevertheless, from the Bloch wave analysis of Lemma 3.1 we deduce

$$\int_\Omega \left(A^\epsilon \nabla\tilde{u}_\epsilon \cdot \nabla\overline{\tilde{u}_\epsilon} + \frac{c^\epsilon - \lambda_1(\theta_0)}{\epsilon^2}\tilde{u}_\epsilon \cdot \overline{\tilde{u}_\epsilon}\right) dx \geq 0,$$

which, combined with (79), yields

$$\epsilon^2 \|\frac{\partial\tilde{u}_\epsilon}{\partial t}\|_{L^\infty((0,T);L^2(\Omega)^K)} \leq C. \tag{80}$$

In a second step we multiply (41) by $\overline{\tilde{u}_\epsilon}$ and we take the imaginary part

$$\begin{aligned}&\sqrt{\lambda_1(\theta_0)}\int_\Omega |\tilde{u}_\epsilon(T)|^2\,dx - \sqrt{\lambda_1(\theta_0)}\int_\Omega |\tilde{u}_\epsilon(0)|^2\,dx \\ &+\epsilon^2\mathcal{I}\left(\int_\Omega \overline{\tilde{u}_\epsilon}(T)\frac{\partial\tilde{u}_\epsilon}{\partial t}(T)\,dx - \int_\Omega \overline{\tilde{u}_\epsilon}(0)\frac{\partial\tilde{u}_\epsilon}{\partial t}(0)\,dx\right) = 0.\end{aligned} \tag{81}$$

Using (80) we deduce from (81)

$$\sqrt{\lambda_1(\theta_0)}\|\tilde{u}_\epsilon(T)\|^2_{L^2(\Omega)^K} \leq C\left(1 + \|\tilde{u}_\epsilon(T)\|_{L^2(\Omega)^K}\right),$$

which implies that $\tilde{u}_\epsilon$ is bounded in $L^\infty\left((0,T);L^2(\Omega)^K\right)$. Remark that (81), unlike (77), does not include any gradient term, so we can not apply Lemma 4.2 to obtain a better estimate. □

7 Generalization to high level bands

We generalize the homogenization of a parabolic system established in Section 3 for initial data concentrating at the bottom of the first Bloch band to

another type of initial data concentrating at the bottom of an higher level band. Such a generalization holds true only in the case of the whole space $\Omega = \mathbb{R}^N$ because otherwise we lack an adequate generalization of the compactness Lemma 4.2. ¿From now on in this section we replace assumption (9) by the following one: for an energy level $n \geq 1$, there exists a Bloch parameter $\theta_0 \in \mathbb{T}^N$ such that

$$\begin{cases} (i) & \theta_0 \text{ is the unique minimizer of } \lambda_n(\theta) \text{ in } \mathbb{T}^N, \\ (ii) & \lambda_n(\theta_0) \text{ is a simple eigenvalue,} \\ (iii) & \text{the Hessian matrix } \nabla_\theta \nabla_\theta \lambda_n(\theta_0) \text{ is positive definite.} \end{cases} \tag{82}$$

Under assumption (82) the n^{th} eigencouple of (8) is analytic at θ_0. It is easily seen that the first derivative $\frac{\partial \psi_n}{\partial \theta_k}$ and the second derivative $\frac{\partial^2 \psi_n}{\partial \theta_k \partial \theta_l}$ satisfy equations similar to (11) and (12) respectively, up to changing the label 1 in n. In particular, for $\theta = \theta_0$ we still use the following notation

$$\frac{\partial \psi_n}{\partial \theta_k} = 2i\pi\zeta_k, \quad \frac{\partial^2 \psi_n}{\partial \theta_k \partial \theta_l} = -4\pi^2 \chi_{kl}. \tag{83}$$

where ζ_k and χ_{kl} are solutions of (14) and (15) respectively, up to changing the label 1 in n.

We study a parabolic system with purely periodic coefficients

$$\begin{cases} \dfrac{\partial u_\epsilon}{\partial t} - \operatorname{div}\left(A\left(\dfrac{x}{\epsilon}\right)\nabla u_\epsilon\right) + \dfrac{c\left(\frac{x}{\epsilon}\right)}{\epsilon^2} u_\epsilon = 0 & \text{in } \mathbb{R}^N \times (0,T), \\ u_\epsilon(t=0,x) = u_\epsilon^0(x) & \text{in } \mathbb{R}^N. \end{cases} \tag{84}$$

We also need an assumption on the initial data which must be "well prepared", namely concentrating at the bottom on the n^{th} Bloch band. Recall from Lemma 2.4 that any function $u_\epsilon^0 \in L^2(\mathbb{R}^N)$ can be decomposed as

$$u_\epsilon^0(x) = \sum_{k \geq 1} \int_{\epsilon^{-1}\mathbb{T}^N} \alpha_k^\epsilon(\eta) \psi_k(\frac{x}{\epsilon}, \theta_0 + \epsilon\eta) e^{2i\pi\eta\cdot x} e^{-2i\pi\frac{\theta_0 \cdot x}{\epsilon}} d\eta,$$

with $\eta = \frac{\theta - \theta_0}{\epsilon}$. We denote by Π_ϵ^n the projection operator on the Bloch bands above the n^{th} level

$$\Pi_\epsilon^n u_\epsilon^0(x) = \sum_{k \geq n} \int_{\epsilon^{-1}\mathbb{T}^N} \alpha_k^\epsilon(\eta) \psi_k(\frac{x}{\epsilon}, \theta_0 + \epsilon\eta) e^{2i\pi\eta\cdot x} e^{-2i\pi\frac{\theta_0 \cdot x}{\epsilon}} d\eta. \tag{85}$$

Our assumption on the initial data is that

$$u_\epsilon^0 = \Pi_\epsilon^n u_\epsilon^0. \tag{86}$$

Typically, we are interested in an initial data of the type

$$u_\epsilon^{0,1}(x) = \Pi_\epsilon^n \left(v^0(x) \psi_n(\frac{x}{\epsilon}, \theta_0) e^{2i\pi \frac{\theta_0 \cdot x}{\epsilon}} \right), \tag{87}$$

with $v^0 \in L^2(\mathbb{R}^N)$. However, since the projection operator Π_ϵ^n is not very explicit, we also consider another type of initial data which satisfies assumption (86), namely

$$u_\epsilon^{0,2}(x) = \int_{\epsilon^{-1}\mathbb{T}^N} \alpha_n(\eta) \psi_n(\frac{x}{\epsilon}, \theta_0 + \epsilon\eta) e^{2i\pi\eta\cdot x} e^{2i\pi \frac{\theta_0 \cdot x}{\epsilon}} d\eta, \tag{88}$$

with $\alpha_n \in L^2(\mathbb{R}^N)$ being the Fourier transform of $v^0(x)$. Actually, it is easy to check that

$$\lim_{\epsilon \to 0} \|u_\epsilon^{0,1} - u_\epsilon^{0,2}\|_{L^2(\mathbb{R}^N)} = 0.$$

For such well-prepared initial data, we perform a time renormalization similar to (18)

$$\tilde{u}_\epsilon(t,x) = e^{\frac{\lambda_n(\theta_0)t}{\epsilon^2}} u_\epsilon(t,x), \tag{89}$$

such that $\tilde{u}_\epsilon$ satisfies

$$\begin{cases} \dfrac{\partial \tilde{u}_\epsilon}{\partial t} - \operatorname{div}\left(A\left(\dfrac{x}{\epsilon}\right) \nabla \tilde{u}_\epsilon \right) + \dfrac{c\left(\frac{x}{\epsilon}\right) - \lambda_n(\theta_0)}{\epsilon^2} \tilde{u}_\epsilon = 0 & \text{in } \mathbb{R}^N \times (0,T), \\ \tilde{u}_\epsilon(t=0,x) = u_\epsilon^0(x) & \text{in } \mathbb{R}^N. \end{cases} \tag{90}$$

Lemma 7.1 *Under assumption (86), the solution of (90) satisfies*

$$\|\tilde{u}_\epsilon\|_{L^\infty((0,T);L^2(\mathbb{R}^N)^K)} + \epsilon \|\nabla \tilde{u}_\epsilon\|_{L^2((0,T)\times\mathbb{R}^N)^{N\times K}} \leq C \|u_\epsilon^0\|_{L^2(\mathbb{R}^N)^K}, \tag{91}$$

and there exists a bounded scalar sequence v_ϵ in $L^2\left((0,T); H^1(\mathbb{R}^N)\right)$ such that

$$\tilde{u}_\epsilon(t,x) = \psi_n\left(\frac{x}{\epsilon}, \theta_0\right) e^{2i\pi \frac{\theta_0 \cdot x}{\epsilon}} v_\epsilon(t,x) + r_\epsilon(t,x), \tag{92}$$

where $\lim_{\epsilon\to 0} \|r_\epsilon\|_{L^2((0,T)\times\omega)^K} = 0$ for any compact set $\omega \subset \mathbb{R}^N$.

Theorem 7.2 *Assume that the initial data $u_\epsilon^0 \in L^2(\mathbb{R}^N)^K$ is of the form (87) or (88). The solution of (84) can be written as*

$$u_\epsilon(t,x) = e^{-\frac{\lambda_n(\theta_0)t}{\epsilon^2}}\left(\psi_n\left(\frac{x}{\epsilon},\theta_0\right)e^{2i\pi\frac{\theta_0\cdot x}{\epsilon}}v_\epsilon(t,x) + r_\epsilon(t,x)\right), \tag{93}$$

where r_ϵ is a remainder term such that

$$\lim_{\epsilon\to 0}\|r_\epsilon\|_{L^2((0,T)\times\omega)^K} = 0 \text{ for any compact set } \omega \subset \mathbb{R}^N, \tag{94}$$

and v_ϵ converges weakly in $L^2\left((0,T);H^1(\mathbb{R}^N)\right)$ to the solution v of the scalar homogenized problem

$$\begin{cases} \dfrac{\partial v}{\partial t} - \operatorname{div}\left(A_n^*\nabla v\right) = 0 & \text{in } \mathbb{R}^N\times(0,T), \\ v(t=0,x) = v^0(x) & \text{in } \mathbb{R}^N, \end{cases} \tag{95}$$

with $A_n^* = \frac{1}{4\pi^2}\nabla_\theta\nabla_\theta\lambda_n(\theta_0)$.

Remark 7.3 *In the context of the Schrödinger equation Theorem 7.2 is called an effective mass theorem [22], [24], [25]. Even in the case of a scalar equation, Theorem 7.2 is new since the factorization principle does not work for an energy level $n > 1$, namely one can not divide the unknown u_ϵ by $\psi_n\left(\frac{x}{\epsilon},\theta_0\right)$ which necessarily vanishes at some points in $\mathbb{T}^N$.*

Remark 7.4 *An initial data of the type (87) or (88) would yield a zero limit if homogenized in the setting of Theorem 3.2. The solution u_ϵ, given by (93), decays much faster than that given by (22) because $\lambda_n(\theta_0) > \lambda_1(\theta_0)$. Therefore, we can interpret Theorem 7.2 as describing initial layers in time, compared to Theorem 3.2 which captures the average behavior. This is consistent with the classical homogenization of parabolic equations, when $c \equiv 0$, where initial layers in time are known to exist [12] but can not be characterized by the classical homogenization theory.*

Proof of Lemma 7.1. We apply the rescaled Bloch decomposition (16) to equation (90)

$$\tilde{u}_\epsilon(t,x) = \sum_{k\geq 1}\int_{\epsilon^{-1}\mathbb{T}^N}\alpha_k^\epsilon(t,\eta)\psi_k(\frac{x}{\epsilon},\theta_0+\epsilon\eta)e^{2i\pi\eta\cdot x}e^{2i\pi\frac{\theta_0\cdot x}{\epsilon}}d\eta,$$

with

$$\alpha_k^\epsilon(t,\eta) = \alpha_k^\epsilon(0,\eta) e^{\frac{(\lambda_n - \lambda_k)(\theta_0+\epsilon\eta)}{\epsilon^2} t}.$$

¿From assumption (86) we deduce that $\alpha_k^\epsilon(t,\eta) = 0$ for any $k < n$. Therefore, for any time t, we have $\Pi_\epsilon^n \tilde{u}_\epsilon(t,x) = \tilde{u}_\epsilon(t,x)$. Thus,

$$\int_{\mathbb{R}^N} \left(A\left(\frac{x}{\epsilon}\right) \nabla \tilde{u}_\epsilon \cdot \nabla \tilde{u}_\epsilon + \frac{c\left(\frac{x}{\epsilon}\right) - \lambda_n(\theta_0)}{\epsilon^2} \tilde{u}_\epsilon \cdot \tilde{u}_\epsilon \right) dx \geq 0,$$

which easily yields the a priori estimate (91). We now mimick the arguments of the proof of Lemma 4.2 (replacing the label 1 by n) to obtain the compactness result (92). □

Proof of Theorem 7.2. The proof is very similar to that of Theorem 3.2 so we simply sketch the main points. We introduce, as before, a sequence w_ϵ defined by

$$w_\epsilon(t,x) = \tilde{u}_\epsilon(t,x) e^{-2i\pi \frac{\theta_0 \cdot x}{\epsilon}}.$$

By the a priori estimates of Lemma 7.1, there exist a subsequence and a limit $w(t,x,y) \in L^2\left((0,T) \times \mathbb{R}^N; H^1(\mathbb{T}^N)^K\right)$ such that w_ϵ and $\epsilon \nabla w_\epsilon$ two-scale converges to w and $\nabla_y w$ respectively [2], [23]). Similarly, by its very definition, $w_\epsilon(0,x)$ two-scale converges to $\psi_n(y,\theta_0)\, v^0(x)$. In a first step we multiply (90) by the complex conjugate of $\epsilon^2 \phi(t,x,\frac{x}{\epsilon}) e^{2i\pi \frac{\theta_0 \cdot x}{\epsilon}}$ where $\phi(t,x,y)$ is a smooth test function defined in $[0,T) \times \mathbb{R}^N \times \mathbb{T}^N$ with values in $\mathbb{C}^K$. Passing to the two-scale limit yields the existence of a scalar function $v(t,x) \in L^2\left((0,T) \times \mathbb{R}^N\right)$ such that $w(t,x,y) = v(t,x)\psi_n(y,\theta_0)$. In a second step we multiply (90) by the complex conjugate of

$$\Psi_\epsilon = e^{2i\pi \frac{\theta_0 \cdot x}{\epsilon}} \left(\psi_n(\frac{x}{\epsilon}, \theta_0)\phi(t,x) + \epsilon \sum_{k=1}^N \frac{\partial \phi}{\partial x_k}(t,x) \zeta_k(\frac{x}{\epsilon}) \right)$$

where $\phi(t,x)$ is a smooth, compactly supported, test function defined from $[0,T) \times \mathbb{R}^N$ into $\mathbb{R}$, and $\zeta_k(y)$ is the solution of (14) where the label 1 is replaced by n. Passing to the two-scale limit yields a very weak form of the homogenized equation (95). It is routine to show that its solution $v(t,x)$ is indeed a classical weak solution. Then, by uniqueness of the solution, we deduce that the entire sequence w_ϵ two-scale converges to $\psi_n(y,\theta_0)\, v(t,x)$. □

Remark 7.5 *All the results of this section are specific to the case of the whole space, i.e.* $\Omega = \mathbb{R}^N$*, and can not be extended to the case of an additional zero-order term* $d(x, \frac{x}{\epsilon})$ *because we crucially use the Bloch diagonalization to get a priori estimates.*

8 Fourth order homogenized problem

By changing the main assumption on the Bloch spectrum it is possible to obtain a fourth order homogenized equation from a second order parabolic problem. Specifically we consider

$$\begin{cases} \epsilon^2 \dfrac{\partial u_\epsilon}{\partial t} - \operatorname{div}\left(A\left(\dfrac{x}{\epsilon}\right)\nabla u_\epsilon\right) + \left(\epsilon^{-2} c\left(\dfrac{x}{\epsilon}\right) + \epsilon^2 d\left(x, \dfrac{x}{\epsilon}\right)\right) u_\epsilon = 0 & \text{in } \Omega \times (0,T), \\ u_\epsilon = 0 & \text{on } \partial\Omega \times (0,T), \\ u_\epsilon(t=0,x) = u_\epsilon^0(x) & \text{in } \Omega. \end{cases} \tag{96}$$

Remark that the time scaling in (96) is not the same than that in (17): this means that we are looking for an asymptotic for longer time of order ϵ^{-2} in (96), compared to (17). Instead of (9), we now make the following assumption

$$\begin{cases} (i) & \theta_0 \text{ is the unique minimizer of } \lambda_1(\theta) \text{ in } \mathbb{T}^N, \\ (ii) & \lambda_1(\theta_0) \text{ is a simple eigenvalue}, \\ (iii) & \nabla_\theta \nabla_\theta \lambda_1(\theta_0) = 0, \\ (iv) & \text{the fourth-order tensor } \nabla_\theta \nabla_\theta \nabla_\theta \nabla_\theta \lambda_1(\theta_0) \text{ is positive definite.} \end{cases} \tag{97}$$

Remark 8.1 *We do not know if assumption (97) is satisfied for any practical example.*

Since $\lambda_1(\theta_0)$ is a minimum, we also have $\nabla_\theta \lambda_1(\theta_0) = 0$ and $\nabla_\theta \nabla_\theta \nabla_\theta \lambda_1(\theta_0) = 0$. Under assumption (97) the first eigencouple of (8) is analytic at θ_0. Recall that, for $\theta = \theta_0$, the two first derivatives of ψ_1 are given by

$$\frac{\partial \psi_1}{\partial \theta_k} = 2i\pi\zeta_k, \quad \frac{\partial^2 \psi_1}{\partial \theta_k \partial \theta_l} = -4\pi^2 \chi_{kl}, \tag{98}$$

where ζ_k is the solution of (14) and χ_{kl} is the solution of (15) (remark that this last equation simplifies since $\nabla_\theta \nabla_\theta \lambda_1(\theta_0) = 0$). Similarly, the third

derivative is

$$\frac{\partial^3 \psi_1}{\partial\theta_j \partial\theta_k \partial\theta_l} = -8i\pi^3 \xi_{jkl}, \tag{99}$$

where

$$\begin{aligned}
\mathbb{A}(\theta_0)\xi_{jkl} &= e_j A(y)(\nabla_y + 2i\pi\theta_0)\chi_{kl} + (\mathrm{div}_y + 2i\pi\theta_0)\left(A(y)e_j\chi_{kl}\right) \\
&+ e_k A(y)(\nabla_y + 2i\pi\theta_0)\chi_{jl} + (\mathrm{div}_y + 2i\pi\theta_0)\left(A(y)e_k\chi_{jl}\right) \\
&+ e_l A(y)(\nabla_y + 2i\pi\theta_0)\chi_{kj} + (\mathrm{div}_y + 2i\pi\theta_0)\left(A(y)e_l\chi_{kj}\right) \\
&+ e_k A(y)e_l\zeta_j + e_j A(y)e_l\zeta_k + e_k A(y)e_j\zeta_l.
\end{aligned} \tag{100}$$

There exists a unique solution of (100), up to the addition of a multiple of ψ_1. Indeed, the right hand side of (100) satisfies the required compatibility condition (i.e. it is orthogonal to ψ_1) because all derivatives of $\lambda_1(\theta)$, up to third order, are zero at $\theta = \theta_0$.

We perform a time renormalization by introducing a new unknown

$$\tilde{u}_\epsilon(t,x) = e^{\frac{\lambda_1(\theta_0)t}{\epsilon^4}} u_\epsilon(t,x), \tag{101}$$

which satisfies

$$\begin{cases}
\dfrac{\partial \tilde{u}_\epsilon}{\partial t} - \epsilon^{-2}\mathrm{div}\left(A\left(\dfrac{x}{\epsilon}\right)\nabla\tilde{u}_\epsilon\right) + \dfrac{c\left(\frac{x}{\epsilon}\right) - \lambda_1(\theta_0)}{\epsilon^4}\tilde{u}_\epsilon + d\left(x, \dfrac{x}{\epsilon}\right)\tilde{u}_\epsilon = 0 & \text{in } \Omega\times(0,T), \\
\tilde{u}_\epsilon = 0 & \text{on } \partial\Omega\times(0,T), \\
\tilde{u}_\epsilon(t=0,x) = u_\epsilon^0(x) & \text{in } \Omega.
\end{cases} \tag{102}$$

As usual we obtain the following a priori estimate

$$\|\tilde{u}_\epsilon\|_{L^\infty((0,T);L^2(\Omega)^K)} + \epsilon\|\nabla\tilde{u}_\epsilon\|_{L^2((0,T)\times\Omega)^{N\times K}} \leq C\|u_\epsilon^0\|_{L^2(\Omega)^K},$$

where the constant $C > 0$ does not depend on ϵ.

Theorem 8.2 *Assume that the initial data $u_\epsilon^0 \in L^2(\Omega)^K$ is of the form*

$$u_\epsilon^0(x) = \psi_1\left(\frac{x}{\epsilon}, \theta_0\right) e^{2i\pi\frac{\theta_0\cdot x}{\epsilon}} v^0(x), \tag{103}$$

with $v^0 \in L^2(\Omega)$. The solution of (96) can be written as

$$u_\epsilon(t,x) = e^{-\frac{\lambda_1(\theta_0)t}{\epsilon^4}}\left(\psi_1\left(\frac{x}{\epsilon}, \theta_0\right) e^{2i\pi\frac{\theta_0\cdot x}{\epsilon}} v_\epsilon(t,x) + r_\epsilon(t,x)\right), \tag{104}$$

where r_ϵ is a remainder term such that

$$\lim_{\epsilon\to 0}\|r_\epsilon\|_{L^2((0,T)\times\omega)^K}=0 \text{ for any compact set } \omega\subset\mathbb{R}^N,$$

and v_ϵ converges weakly in $L^2\left((0,T);H^2(\Omega)\right)$ to the solution v of the scalar fourth-order homogenized problem

$$\begin{cases} \dfrac{\partial v}{\partial t}+\operatorname{div}\operatorname{div}\left(A^*\nabla\nabla v\right)=0 & \text{in } \Omega\times(0,T),\\ \dfrac{\partial v}{\partial n}=v=0 & \text{on } \partial\Omega\times(0,T),\\ v(t=0,x)=v^0(x) & \text{in } \Omega, \end{cases} \tag{105}$$

with $A^*=\frac{1}{16\pi^4}\nabla_\theta\nabla_\theta\nabla_\theta\nabla_\theta\lambda_1(\theta_0)$.

To prove Theorem 8.2 we need the following generalization of Lemma 4.2.

Lemma 8.3 *Let u_ϵ be a bounded sequence in $L^2(\mathbb{R}^N)^K$. Assume that there exists a finite constant C such that*

$$\int_{\mathbb{R}^N}\left(A\left(\frac{x}{\epsilon}\right)\nabla u_\epsilon\cdot\nabla u_\epsilon+\frac{c\left(\frac{x}{\epsilon}\right)-\lambda_1(\theta_0)}{\epsilon^2}u_\epsilon\cdot u_\epsilon\right)dx\le C\epsilon^2. \tag{106}$$

Then, under assumption (97),

$$u_\epsilon(x)=\psi_1\left(\frac{x}{\epsilon},\theta_0\right)e^{2i\pi\frac{\theta_0\cdot x}{\epsilon}}v_\epsilon(x)+r_\epsilon(x), \tag{107}$$

where v_ϵ is a bounded scalar sequence in $H^2(\mathbb{R}^N)$ and $\lim_{\epsilon\to 0}\|r_\epsilon\|_{L^2(\omega)^K}=0$ for any compact set $\omega\subset\mathbb{R}^N$.

Proof. Introducing the rescaled Bloch decomposition (16) of $u_\epsilon(x)$ with $\eta=\frac{\theta-\theta_0}{\epsilon}$,

$$u_\epsilon(x)=\sum_{k\ge 1}\int_{\epsilon^{-1}\mathbb{T}^N}\alpha_k^\epsilon(\eta)\psi_k(\frac{x}{\epsilon},\theta_0+\epsilon\eta)e^{2i\pi\eta\cdot x}e^{2i\pi\frac{\theta_0\cdot x}{\epsilon}}d\eta,$$

the same arguments than those in the proof of Lemma 4.2 and the estimate

$$\lambda_1(\theta)-\lambda_1(\theta_0)\ge C|\theta-\theta_0|^4\quad\forall\theta\in\mathbb{T}^N,$$

shows that

$$\int_{\epsilon^{-1}\mathbb{T}^N} |\eta|^4 |\alpha_1^\epsilon(\eta)|^2 d\eta \leq C.$$

Defining $v_\epsilon(x)$ as the inverse Fourier transform of $\alpha_1^\epsilon(\eta)$, we deduce that v_ϵ is uniformly bounded in $H^2(\mathbb{R}^N)$. $\square$

Proof of Theorem 8.2. The proof is similar to that of Theorem 3.2. The first step is identical: the function $w_\epsilon(t,x) = u_\epsilon(t,x)e^{-2i\pi\frac{\theta_0\cdot x}{\epsilon}}$ two-scale converges to a limit $v(t,x)\psi_1(y,\theta_0)$. In the second step, we multiply (102) by the complex conjugate of

$$\begin{aligned}\Psi_\epsilon = \; & e^{2i\pi\frac{\theta_0\cdot x}{\epsilon}}\left(\psi_1(\frac{x}{\epsilon},\theta_0)\phi(t,x) + \epsilon\sum_{k=1}^N \frac{\partial\phi}{\partial x_k}(t,x)\zeta_k(\frac{x}{\epsilon})\right.\\ & \left. +\epsilon^2\sum_{k,l=1}^N \frac{\partial^2\phi}{\partial x_k\partial x_l}(t,x)\chi_{kl}(\frac{x}{\epsilon}) + \epsilon^3\sum_{j,k,l=1}^N \frac{\partial^3\phi}{\partial x_j\partial x_k\partial x_l}(t,x)\xi_{jkl}(\frac{x}{\epsilon})\right),\end{aligned} \tag{108}$$

where $\phi(t,x)$ is a smooth, compactly supported, test function defined from $[0,T)\times\Omega$ into $\mathbb{R}$, $\zeta_k(y)$ is the solution of (14), $\chi_{kl}(y)$ is the solution of (15), and $\xi_{jkl}(y)$ is the solution of (100). After some tedious algebra we find that

$$\begin{aligned}&\int_\Omega |\psi_1^\epsilon|^2 v^0\overline{\phi}(0)\,dx - \int_0^T\int_\Omega w_\epsilon\cdot\overline{\psi}_1^\epsilon\frac{\partial\overline{\phi}}{\partial t}\,dt\,dx\\ &-\int_0^T\int_\Omega A^\epsilon w_\epsilon\nabla\frac{\partial^3\overline{\phi}}{\partial x_j\partial x_k\partial x_l}\cdot e_k\overline{\chi}_{jl}^\epsilon\,dt\,dx\\ &-\int_0^T\int_\Omega A^\epsilon w_\epsilon\nabla\frac{\partial^3\overline{\phi}}{\partial x_j\partial x_k\partial x_l}\cdot(\epsilon\nabla - 2i\pi\theta_0)\overline{\eta}_{jkl}^\epsilon\,dt\,dx\\ &+\int_0^T\int_\Omega A^\epsilon\overline{\eta}_{jkl}^\epsilon(\epsilon\nabla + 2i\pi\theta_0)w_\epsilon\cdot\nabla\frac{\partial^3\overline{\phi}}{\partial x_j\partial x_k\partial x_l}\,dt\,dx\\ &+\int_0^T\int_\Omega d^\epsilon w_\epsilon\cdot\overline{\psi}_1^\epsilon\overline{\phi}\,dt\,dx = \mathcal{O}(\epsilon).\end{aligned} \tag{109}$$

Passing to the two-scale limit in each term of (109) gives

$$\begin{aligned}
&\int_\Omega \int_{\mathbb{T}^N} |\psi_1|^2 v^0 \overline{\phi}(0)\, dx\, dy - \int_0^T \int_\Omega \int_{\mathbb{T}^N} |\psi_1|^2 v \frac{\partial \overline{\phi}}{\partial t} dt\, dx\, dy \\
&- \int_0^T \int_\Omega \int_{\mathbb{T}^N} A\psi_1 v \nabla \frac{\partial^3 \overline{\phi}}{\partial x_j \partial x_k \partial x_l} \cdot e_k \overline{\chi}_{jl}\, dt\, dx\, dy \\
&- \int_0^T \int_\Omega \int_{\mathbb{T}^N} A\psi_1 v \nabla \frac{\partial^3 \overline{\phi}}{\partial x_j \partial x_k \partial x_l} \cdot (\nabla_y - 2i\pi\theta_0)\overline{\eta}_{jkl}\, dt\, dx\, dy \qquad (110) \\
&+ \int_0^T \int_\Omega \int_{\mathbb{T}^N} A\overline{\eta}_{jkl}(\nabla_y + 2i\pi\theta_0)\psi_1 v \cdot \nabla \frac{\partial^3 \overline{\phi}}{\partial x_j \partial x_k \partial x_l}\, dt\, dx\, dy \\
&+ \int_0^T \int_\Omega \int_{\mathbb{T}^N} d\psi_1 v \cdot \overline{\psi}_1 \overline{\phi}\, dt\, dx\, dy \qquad = 0.
\end{aligned}$$

Recalling the normalization $\int_{\mathbb{T}^N} |\psi_1|^2 dy = 1$, and introducing

$$\begin{aligned}
A^*_{jklm} = \int_{\mathbb{T}^N} \Big(&- A\psi_1 e_m \cdot e_k \overline{\chi}_{jl} - A\psi_1 e_m \cdot (\nabla_y - 2i\pi\theta_0)\overline{\eta}_{jkl} \\
&+ A\overline{\eta}_{jkl}(\nabla_y + 2i\pi\theta_0)\psi_1 \cdot e_m \Big) dy
\end{aligned} \qquad (111)$$

(which has to be symmetrized), and $d^*(x) = \int_{\mathbb{T}^N} d(x,y)\psi_1(y) \cdot \overline{\psi}_1(y)\, dy$, (110) is equivalent to

$$\int_\Omega v^0 \overline{\phi}(0)\, dx - \int_0^T \int_\Omega \left(v \frac{\partial \overline{\phi}}{\partial t} - A^* v \cdot \nabla\nabla\nabla\nabla \overline{\phi} - d^*(x) v \overline{\phi} \right) dt\, dx = 0$$

which is a very weak form of the homogenized equation (105). To recover the Dirichlet boundary condition, we use Lemma 8.3 which implies that $v \in H^2(\mathbb{R}^N)$ and $v = 0$ in any compact set $\omega \subset \big(\mathbb{R}^N \setminus \Omega\big)$. Thus v belongs to $H^2_0(\Omega)$.

The compatibility condition of the equation giving the fourth derivative of ψ_1 yields that the tensor A^*, defined by (111), is indeed equal to $\frac{1}{16\pi^4}\nabla_\theta\nabla_\theta\nabla_\theta\nabla_\theta\lambda_1(\theta_0)$, and thus is real, symmetric, positive definite by assumption (97). Therefore, the homogenized problem (105) is well posed. By uniqueness of the solution, the entire sequence v_ϵ converges to v. □

9 Homogenization of a fourth-order equation

Our method also applies to fourth-order problems. Although systems of equations can be treated, for simplicity we focus on the case of a single

equation, without loss of generality since there is no maximum principle for fourth-order elliptic equation. Let us introduce the following symmetric fourth-order operator

$$\mathcal{A}^\epsilon = \operatorname{div}\operatorname{div}\left(\Theta(\frac{x}{\epsilon})\nabla\nabla\right) - \frac{1}{\epsilon^2}\operatorname{div}\left(A(\frac{x}{\epsilon})\nabla\right) + \frac{1}{\epsilon^4}c(\frac{x}{\epsilon}) + d(x,\frac{x}{\epsilon}), \qquad (112)$$

with periodic coefficients $\Theta(y) = \{\Theta_{ijkl}(y)\}$, $A(y) = \{A_{ij}(y)\}$ and $c(y)$ which are real periodic functions in $L^\infty(\mathbb{T}^N)$. Furthermore, Θ and A are symmetric tensors, and Θ is uniformly elliptic. The locally periodic term $d(x,y)$ belongs to $L^\infty\left(\Omega; C(\mathbb{T}^N)\right)$.

Under these assumptions the Bloch decomposition for (112) is basically the same as that for second order operators. On the torus $\mathbb{T}^N$ we introduce the Bloch operators

$$\mathcal{A}(\theta)\psi(y) = e^{-2i\pi y\cdot\theta}\mathcal{A}e^{-2i\pi y\cdot\theta}\psi(y) =$$

$$(\nabla_y + 2i\pi\theta)(\nabla_y + 2i\pi\theta)\cdot(\Theta(y)(\nabla_y + 2i\pi\theta)(\nabla_y + 2i\pi\theta))\psi(y) +$$
$$-(\nabla_y + 2i\pi\theta)\cdot(A(y)(\nabla_y + 2i\pi\theta)\psi(y) + c(y)\psi(y),$$

with $\mathcal{A} = \operatorname{div}\operatorname{div}(\Theta(y)\nabla\nabla) - \operatorname{div}(A(y)\nabla) + c(y)$. Then, the Bloch spectral cell problem

$$\mathcal{A}(\theta)\psi_n = \lambda_n(\theta)\psi_n \quad \text{in} \quad L^2(\mathbb{T}^N)$$

has a discrete spectrum $\lambda_1(\theta) \le \lambda_2(\theta) \le \ldots \le \lambda_n(\theta) \to +\infty$. Moreover, all the statements of Lemma 2.4 (and its rescaled version) remain valid.

It is quite natural to make assumption (97) which implies $\nabla_\theta\nabla_\theta\lambda_1(\theta_0) = 0$. For example, (97) is easily seen to be satisfied with $\theta_0 = 0$ if there are no zero and second order terms in (112), i.e. $A \equiv 0$, $c \equiv 0$.

We begin with the parabolic Cauchy problem

$$\begin{cases} \dfrac{\partial u_\epsilon}{\partial t} + \mathcal{A}^\epsilon u_\epsilon = 0 & \text{in } \Omega\times(0,T), \\ u_\epsilon = 0, \quad \dfrac{\partial u_\epsilon}{\partial n} = 0 & \text{on } \partial\Omega\times(0,T), \\ u_\epsilon(t=0,x) = u_\epsilon^0(x) & \text{in } \Omega. \end{cases} \qquad (113)$$

Theorem 9.1 *Assume (97). Let $u_\epsilon(t,x)$ be a solution of (113) with $\mathcal{A}^\epsilon$ given by (112), and $u_\epsilon^0 \in L^2(\Omega)$ be an initial data of the form*

$$u_\epsilon^0(x) = \psi_1\left(\frac{x}{\epsilon},\theta_0\right)e^{2i\pi\frac{\theta_0\cdot x}{\epsilon}}v^0(x),$$

with $v^0 \in L^2(\Omega)$. Then u_ϵ can be written as

$$u_\epsilon(t,x) = e^{-\frac{\lambda_1(\theta_0)t}{\epsilon^4}}\left(\psi_1\left(\frac{x}{\epsilon},\theta_0\right)e^{2i\pi\frac{\theta_0\cdot x}{\epsilon}}v_\epsilon(t,x) + r_\epsilon(t,x)\right),$$

where the remainder term r_ϵ satisfies the relation

$$\lim_{\epsilon\to 0}\|r_\epsilon\|_{L^2((0,T)\times\omega)} = 0 \text{ for any compact set } \omega \subset \mathbb{R}^N,$$

and v_ϵ converges weakly in $L^2\left((0,T);H^2(\Omega)\right)$ to the solution v of

$$\begin{cases} \dfrac{\partial v}{\partial t} + \mathcal{A}^* v = 0 & \text{in } \Omega\times(0,T), \\ v = 0, \quad \dfrac{\partial v}{\partial n} = 0 & \text{on } \partial\Omega\times(0,T), \\ v(t=0,x) = v^0(x) & \text{in } \Omega, \end{cases}$$

with the homogenized operator

$$\mathcal{A}^* = \operatorname{div}\operatorname{div}\left(\Theta^*\nabla\nabla\right) + d^*(x) \tag{114}$$

and $\Theta^* = \frac{1}{16\pi^4}\nabla_\theta\nabla_\theta\nabla_\theta\nabla_\theta\lambda_1(\theta_0)$, $d^*(x) = \int_{\mathbb{T}^N} d(x,y)|\psi_1(y,\theta_0)|^2 dy$.

The proof of Theorem 9.1 is very similar to that of Theorem 8.2. Upon defining $\tilde{u}^\epsilon(t,x) = e^{\frac{\lambda_1(\theta_0)t}{\epsilon^4}}u^\epsilon(t,x)$, the a priori estimates are

$$\|\tilde{u}^\epsilon\|_{L^2(\Omega)} + \epsilon\|\nabla\tilde{u}^\epsilon\|_{L^2(\Omega)^N} + \epsilon^2\|\nabla\nabla\tilde{u}^\epsilon\|_{L^2(\Omega)^{N^2}} \le C,$$

which, up to a subsequence, implies the following two-scale convergences for $w^\epsilon = e^{-2i\pi x\cdot\theta_0/\epsilon}\tilde{u}^\epsilon(t,x)$

$$w^\epsilon \overset{2s}{\rightharpoonup} v(t,x)\psi_1(y,\theta_0), \quad \epsilon\nabla w^\epsilon \overset{2s}{\rightharpoonup} v(t,x)\nabla_y\psi_1(y,\theta_0), \quad \epsilon^2\nabla\nabla w^\epsilon \overset{2s}{\rightharpoonup} v(t,x)\nabla_y\nabla_y\psi_1(y,\theta_0)$$

where $v(t,x)$ is a limit point of a sequence v^ϵ, bounded in $L^2\left((0,T);H^2(\mathbb{R}^N)\right)$, introduced in a variant of Lemmas 4.2 and 8.3. Eventually, we use the same test function defined in (108). We safely leave the details to the reader.

We then study the Dirichlet spectral problem

$$\mathcal{A}^\epsilon u_n^\epsilon = \lambda_n^\epsilon u_n^\epsilon, \quad u_n^\epsilon \in H_0^2(\Omega)$$

stated in a bounded domain $\Omega \subset \mathbb{R}^N$, which, under the standing ellipticity assumptions, admits a discrete spectrum, $\lambda_n^\epsilon \to +\infty$ as $n \to +\infty$, with corresponding normalized eigenfunctions denoted by u_n^ϵ.

Theorem 9.2 *Assume (97). Then for any $n \geq 1$*

$$\lambda_n^\epsilon = \frac{\lambda_1(\theta_0)}{\epsilon^4} + \mu_n + o(1) \qquad as\ \epsilon \to 0$$

and the corresponding eigenfunction $u_n^\epsilon(x)$ admits the representation

$$u_n^\epsilon(x) = \psi_1\left(\frac{x}{\epsilon}, \theta_0\right) e^{2i\pi\frac{\theta_0 \cdot x}{\epsilon}} v_n^\epsilon(x) + r_n^\epsilon(x), \tag{115}$$

where

$$\lim_{\epsilon\to 0} \|r_n^\epsilon\|_{L^2(\Omega)} = 0, \quad \|v_n^\epsilon\|_{H^2(\Omega)} \leq C, \quad \lim_{\epsilon\to 0} \|v_n^\epsilon\|_{L^2(\Omega)} = 1, \tag{116}$$

and the family v_n^ϵ is relatively compact in $L^2(\Omega)$. Moreover, any limit point v_n^0, as $\epsilon \to 0$, of the sequence v_n^ϵ is a normalized eigenfunction associated to the n-th eigenvalue μ_n of the scalar homogenized spectral problem

$$\mathcal{A}^* v = \mu v \qquad in\ \Omega, \qquad v \in H_0^2(\Omega),$$

with $\mathcal{A}^*$ defined by (114). If μ_n is a simple eigenvalue of the latter problem, the entire sequence v_n^ϵ converges to the homogenized eigenfunction v_n.

The proof is a combination of those of Theorems 3.6 and 8.2. The crucial point is to obtain a uniform estimate for the energy $(\mathcal{A}^\epsilon u_n^\epsilon, u_n^\epsilon)$. To this end we use a test function of the type of (108).

Finally, for the hyperbolic system

$$\begin{cases} \dfrac{\partial^2 u_\epsilon}{\partial t^2} + \mathcal{A}^\epsilon u_\epsilon = 0 & \text{in } \Omega \times (0,T), \\ u_\epsilon = 0, \quad \dfrac{\partial u_\epsilon}{\partial n} = 0 & \text{on } \partial\Omega \times (0,T), \\ u_\epsilon(0,x) = u_\epsilon^0(x) & \text{in } \Omega, \\ \dfrac{\partial u_\epsilon}{\partial t}(0,x) = u_\epsilon^1(x) & \text{in } \Omega, \end{cases} \tag{117}$$

we obtain different homogenized limits according to the sign of $\lambda_1(\theta_0)$.

Theorem 9.3 *Let (97) be fulfilled, and assume that $\lambda_1(\theta_0) = 0$ and the initial data are*

$$u_\epsilon^0(x) = \psi_1\left(\frac{x}{\epsilon}, \theta_0\right) e^{2i\pi\frac{\theta_0 \cdot x}{\epsilon}} v^0(x) \in H_0^2(\Omega),$$
$$u_\epsilon^1(x) = \psi_1\left(\frac{x}{\epsilon}, \theta_0\right) e^{2i\pi\frac{\theta_0 \cdot x}{\epsilon}} v^1(x) \in L^2(\Omega),$$

with $v^0 \in H_0^2(\Omega)$ and $v^1 \in L^2(\Omega)$. The solution of (117), with $\mathcal{A}^\epsilon$ given by (112), can be written as

$$u_\epsilon(t,x) = \psi_1\left(\frac{x}{\epsilon}, \theta_0\right) e^{2i\pi \frac{\theta_0 \cdot x}{\epsilon}} v_\epsilon(t,x) + r_\epsilon(t,x),$$

where the remainder term r_ϵ satisfies the relation

$$\lim_{\epsilon \to 0} \|r_\epsilon\|_{L^2((0,T)\times\omega)} = 0 \text{ for any compact set } \omega \subset \mathbb{R}^N,$$

and v_ϵ converges weakly in $L^2\left((0,T); H^2(\Omega)\right)$ to the solution v of

$$\begin{cases} \dfrac{\partial^2 v}{\partial t^2} + \mathcal{A}^* v = 0 & \text{in } \Omega \times (0,T), \\ v = 0, \quad \dfrac{\partial v}{\partial n} = 0 & \text{on } \partial\Omega \times (0,T), \\ v(t=0,x) = v^0(x) & \text{in } \Omega, \\ \frac{\partial v}{\partial t}(t=0,x) = v^1(x) & \text{in } \Omega, \end{cases}$$

with $\mathcal{A}^*$ defined by (114).

The proof is the same as that of Theorem 3.7. If $\lambda_1(\theta_0) \neq 0$, then we need to look at a different time scaling. Instead of (117), we now consider

$$\begin{cases} \epsilon^4 \dfrac{\partial^2 u_\epsilon}{\partial t^2} + \mathcal{A}^\epsilon u_\epsilon = 0 & \text{in } \Omega \times (0,T), \\ u_\epsilon = 0, \quad \dfrac{\partial u_\epsilon}{\partial n} = 0 & \text{on } \partial\Omega \times (0,T), \\ u_\epsilon(0,x) = u_\epsilon^0(x) & \text{in } \Omega, \\ \dfrac{\partial u_\epsilon}{\partial t}(0,x) = u_\epsilon^1(x) & \text{in } \Omega, \end{cases} \tag{118}$$

Theorem 9.4 *Let (97) be fulfilled, and assume that the initial data are*

$$u_\epsilon^0(x) = \psi_1\left(\frac{x}{\epsilon}, \theta_0\right) e^{2i\pi \frac{\theta_0 \cdot x}{\epsilon}} v^0(x) \in H_0^2(\Omega),$$

with $v^0 \in H_0^2(\Omega)$, and that $\epsilon^4 u_\epsilon^1(x)$ is bounded in $L^2(\Omega)$ while $\epsilon^4 \psi_1\left(\frac{x}{\epsilon}, \theta_0\right) u_\epsilon^1(x)$ converges weakly to 0 in $L^2(\Omega)$.

If $\lambda_1(\theta_0) < 0$ the solution of (118) can be written as

$$u_\epsilon(t,x) = e^{\frac{\sqrt{-\lambda_1(\theta_0)}t}{\epsilon^4}} \left(\psi_1\left(\frac{x}{\epsilon}, \theta_0\right) e^{2i\pi \frac{\theta_0 \cdot x}{\epsilon}} v_\epsilon(t,x) + r_\epsilon(t,x)\right),$$

where $\lim_{\epsilon\to 0}\|r_\epsilon\|_{L^2((0,T)\times\omega)}=0$ *for any compact set* $\omega\subset\mathbb{R}^N$*, and* v_ϵ *converges weakly in* $L^2\left((0,T);H^2(\Omega)\right)$ *to the solution* v *of*

$$\begin{cases} 2\sqrt{-\lambda_1(\theta_0)}\dfrac{\partial v}{\partial t}+\mathcal{A}^*v=0 & \text{in } \Omega\times(0,T),\\ v=0,\quad \dfrac{\partial v}{\partial n}=0 & \text{on } \partial\Omega\times(0,T),\\ v(t=0,x)=\frac{1}{2}v^0(x) & \text{in } \Omega. \end{cases}$$

If $\lambda_1(\theta_0)>0$ *the solution of (118) satisifies*

$$u_\epsilon(t,x)=e^{i\frac{\sqrt{\lambda_1(\theta_0)}t}{\epsilon^4}}e^{2i\pi\frac{\theta_0\cdot x}{\epsilon}}v_\epsilon(t,x),$$

where v_ϵ *two-scale converges to* $\psi_1(y,\theta_0)v(t,x)$ *and* $v\in L^2\left((0,T);H_0^2(\Omega)\right)$ *is the solution of*

$$\begin{cases} 2i\sqrt{\lambda_1(\theta_0)}\dfrac{\partial v}{\partial t}+\mathcal{A}^*v=0 & \text{in } \Omega\times(0,T),\\ v=0,\quad \dfrac{\partial v}{\partial n}=0 & \text{on } \partial\Omega\times(0,T),\\ v(t=0,x)=\frac{1}{2}v^0(x) & \text{in } \Omega, \end{cases}$$

with $\mathcal{A}^*$ *defined by (114).*

Again the proof is similar to those of Theorems 3.8 and 3.10.

Assumption (97) is not the only possible one. In particular, it may happen that $\nabla_\theta\nabla_\theta\lambda_1(\theta_0)$ does not vanish at the minimum value θ_0. Therefore, we now make assumption (9), i.e. $\nabla_\theta\nabla_\theta\lambda_1(\theta_0)$ is positive definite instead of (97).

Remark 9.5 *We give an explicit example where (9) is satisfied rather than (97). Consider an arbitrary periodic, symmetric, uniformly elliptic, operator* $\mathcal{B}$ *of the form* $\mathcal{B}=-\mathrm{div}_y(B(y)\nabla_y)+c(y)$ *and its Bloch spectrum* $\mu_1(\theta)\leq\mu_2(\theta)\leq\dots$*. Adding, if necessary, a sufficiently large positive constant to* c*, we can assume that* $\mu_1(\theta)\geq C>0$*. Considering the relation*

$$\left(e^{-2i\pi y\cdot\theta}\mathcal{B}^2e^{-2i\pi y\cdot\theta}\right)\psi=\left(e^{-2i\pi y\cdot\theta}\mathcal{B}e^{-2i\pi y\cdot\theta}\right)\left(e^{-2i\pi y\cdot\theta}\mathcal{B}e^{-2i\pi y\cdot\theta}\right)\psi$$

we conclude that the Bloch spectrum of the operator $\mathcal{A}=\mathcal{B}^2$ *is* $\left(\lambda_n(\theta)=\mu_n^2(\theta)\right)_{n\geq1}$*. According to Remark 2.1 the unique minimum point of* μ_1 *is attained at* $\theta_0=0$ *and the matrix* $\nabla_\theta\nabla_\theta\mu_1(0)$ *is positive definite. Since* $\mu_1(\theta)$ *is strictly positive, the function* $\lambda_1(\theta)=\mu_1^2(\theta)$ *also has a unique minimum point at* $\theta_0=0$ *and its Hessian at* 0 *is positive definite.*

Under assumption (9) we need to change the scaling of (112) and consider instead the new operator

$$\mathcal{A}^\epsilon = \epsilon^2 \mathrm{div}\,\mathrm{div}\left(\Theta(\frac{x}{\epsilon})\nabla\nabla\right) - \mathrm{div}\left(A(\frac{x}{\epsilon})\nabla\right) + \frac{1}{\epsilon^2}c(\frac{x}{\epsilon}) + d(x,\frac{x}{\epsilon}). \qquad (119)$$

Then, the homogenization of the parabolic equation is given by a result similar to Theorem 3.2.

Theorem 9.6 *Assume (9). Let $u_\epsilon(t,x)$ be a solution of the parabolic equation (113) with $\mathcal{A}^\epsilon$ given by (119), and $u_\epsilon^0 \in L^2(\Omega)$ be an initial data of the form*

$$u_\epsilon^0(x) = \psi_1\left(\frac{x}{\epsilon},\theta_0\right) e^{2\pi i \frac{\theta_0\cdot x}{\epsilon}} v^0(x),$$

with $v^0 \in L^2(\Omega)$. Then u_ϵ can be written as

$$u_\epsilon(t,x) = e^{-\frac{\lambda_1(\theta_0)t}{\epsilon^2}}\left(\psi_1\left(\frac{x}{\epsilon},\theta_0\right) e^{2i\pi\frac{\theta_0\cdot x}{\epsilon}} v_\epsilon(t,x) + r_\epsilon(t,x)\right),$$

where the remainder term r_ϵ satisfies

$$\lim_{\epsilon\to 0} \|r_\epsilon\|_{L^2((0,T)\times\omega)} = 0$$

on any compact set $\omega \subset \mathbb{R}^N$, and v_ϵ converges weakly in $L^2\left((0,T);H^1(\Omega)\right)$ to the solution v of the scalar homogenized problem

$$\begin{cases} \dfrac{\partial v}{\partial t} - \mathrm{div}\left(A^*\nabla v\right) + d^*(x)\, v = 0 & \text{in } \Omega\times(0,T), \\ v = 0 & \text{on } \partial\Omega\times(0,T), \\ v(0,x) = v^0(x) & \text{in } \Omega, \end{cases}$$

with $A^* = \frac{1}{4\pi^2}\nabla_\theta\nabla_\theta\lambda_1(\theta_0)$ and $d^*(x) = \int_{\mathbb{T}^N} d(x,y)|\psi_1(y,\theta_0)|^2 dy$.

The proof of Theorem 9.6 relies on the same test function than in the proof of Theorem 3.2. It should be noted that although $u^\epsilon(t,x)$ belongs to $L^2\left((0,T);H_0^2(\Omega)\right)$, the sequence v^ϵ, defined in Theorem 9.6, is only bounded in $L^2\left((0,T);H^1(\mathbb{R}^N)\right)$, uniformly with respect to ϵ. This is due to assumption (9) which allows us to prove Lemma 4.2 but not Lemma 8.3.

Of course, similar results can be obtained for the spectral problem and for the hyperbolic equation: in both cases the homogenized operator is of second-order in space as in Theorem 9.6.

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