

# Time harmonic Maxwell's equations in periodic waveguides

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# Time harmonic Maxwell's equations in periodic waveguides

A. Kirsch<sup>1</sup> and B. Schweizer<sup>2</sup>

**Abstract:** We study Maxwell's equations with periodic coefficients in a closed waveguide. A functional analytic approach is used to formulate and to solve the radiation problem. We furthermore characterize the set of all bounded solutions to the homogeneous problem. The case of a compact perturbation of the medium is included, the scattering problem and the limiting absorption principle are discussed.

**MSC:** 35Q61

## 1. INTRODUCTION

Maxwell's equations describe electromagnetic waves with the two unknown fields  $E$  and  $H$ . When the frequency  $\omega > 0$  is prescribed, one can use the time-harmonic equations. We regard the permittivity  $\varepsilon$  as complex-valued in order to model conductivity. With two coefficients  $\mu = \mu(x)$  (permeability) and  $\varepsilon = \varepsilon(x)$  (permittivity), both depending on the spatial position  $x \in \mathbb{R}^3$ , the system reads

$$(1.1) \quad \begin{aligned} \operatorname{curl} E &= i\omega\mu H + f_h, \\ \operatorname{curl} H &= -i\omega\varepsilon E + f_e. \end{aligned}$$

Here,  $f_e = f_e(x)$  models prescribed external currents and  $f_h = f_h(x)$  a right hand side in the  $E$ -equation. We include  $f_h$  for mathematical completeness and allow  $\operatorname{div} f_h \neq 0$  in our mathematical analysis below. This will be technically helpful at a later point in the proofs. The inhomogeneities create the fields  $E = E(x)$  and  $H = H(x)$ . We are interested in a waveguide geometry and treat the equations on a domain  $\Omega = \mathbb{R} \times S \subset \mathbb{R}^3$ , where  $S \subset \mathbb{R}^2$  is a bounded Lipschitz domain. We assume that  $\varepsilon, \mu \in L^\infty(\Omega, \mathbb{R})$  are bounded from below by some constant  $c_0 > 0$  and that  $\varepsilon$  and  $\mu$  are  $2\pi$ -periodic with respect to  $x_1$ . Along the exterior boundary, we consider a perfect conductor:  $\nu \times E = 0$  on  $\partial\Omega$  for the exterior unit normal vector  $\nu = \nu(x)$ .

**1.1. Literature.** Electromagnetic waves are described by Maxwell's equations, we refer to [14] for background and an overview over mathematical methods. In applications, one can often assume that the temporal frequency of solutions is fixed and uses the ansatz  $u(x, t) = u(x)e^{-i\omega t}$ . This ansatz leads from Maxwell's equations to the time harmonic Maxwell system (1.1), just as it leads from the wave equation to the Helmholtz equation. Solutions of both, the time harmonic Maxwell system and the Helmholtz equation, describe waves in a medium. When the underlying domain is unbounded, one typically has to complement the system with a radiation condition. The physically relevant condition is, loosely speaking, that energy should be transported to infinity.

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The Helmholtz equation is, in some particular situation, a special case of the Maxwell system. It is therefore not surprising that the appearing phenomena and the analytical methods are very similar.

Of particular interest are waveguides with periodic coefficients. An analysis of the corresponding Helmholtz problem, along with the adequate radiation conditions, is given in [10]. We note that a more functional analytic approach for the same problem was developed in [15, 16], simplified proofs and strengthened results can be found in [17]. These approaches are all containing also results on a limiting absorption principle. Even though the constructions are different, the approaches are all based on the Floquet-Bloch transform, we refer to [18, 21] for more material on this technique.

Some closely related publications, still for the Helmholtz equation, are the following: A semi-infinite waveguide is treated in [13], once more, alongside a limiting absorption principle. An existence result that does not use the Floquet-Bloch transform is given in [25] without limiting absorption principle. Another form of the radiation condition in terms of Bloch waves is developed in [20]. A related approach is studied in [7]. In periodic media, domain truncation can be used to derive an equivalent formulation of the problem on a bounded domain, by using Dirichlet-to-Neumann boundary conditions; for this powerful method we mention [9, 11] and refer to references therein.

Regarding the Maxwell system, we are not aware of investigations of the radiation problem in waveguides with periodic media. One subject of research are scattering problems in the time harmonic setting, see [3, 6], or [2] for a study with Bloch waves. Another subject are numerical methods in waveguide geometries, e.g., in [12]. A nonlinear material (the material cannot be given simply by factors  $\varepsilon$  and  $\mu$ ) is studied in a geometry  $(0, h) \times \mathbb{R}^2$  in [27].

Another topic about the Maxwell system is the regularity of solutions, we refer to [1, 8] for related results. We mention that such topics are closely related to compactness issues, which are very important in our approach.

Finally, there is the large topic of homogenization. In this context, one studies periodic media in the limit that the periodicity length converges to zero. This is an interesting limit which leads to effective theories which can have very surprising features such as negative index materials [4, 19, 22]. A related topic is the question whether or not waves, described by Maxwell's equations, can pass through thin layers of material with small holes, see [5, 26]. We note that these works study either bounded domains or assume boundedness of the solution sequence; in this sense, the results at hand can help to find homogenization limits in more general situations.

**1.2. Variational formulation of the problem.** Let us first make clear how we understand system (1.1). We search for  $E, H \in L^2_{\text{loc}}(\bar{\Omega}, \mathbb{C}^3)$  such that the distributional rotation of  $H$  satisfies  $\text{curl } H \in L^2_{\text{loc}}(\bar{\Omega}, \mathbb{C}^3)$ . For the weak formulation of the system we introduce the space of functions  $H^1_{\text{cpt}}(\Omega)$  which consists of those functions  $\psi : \Omega \rightarrow \mathbb{C}^3$  of class  $H^1(\Omega)$  that are, for some  $R > 0$ , vanishing outside the set  $\Omega_R := (-R, R) \times S$ . We interpret the first equation of (1.1) as

$$(1.2) \quad \int_{\Omega} E \cdot \text{curl } \psi = \int_{\Omega} [i\omega\mu H + f_h] \cdot \psi \quad \text{for every } \psi \in H^1_{\text{cpt}}(\Omega),$$

and emphasize that this formulation encodes also the boundary condition  $E \times \nu = 0$  on  $\partial\Omega$ . The second equation of (1.1) is interpreted as equality of  $L^2_{\text{loc}}$ -functions. In order to illustrate the symmetry in the equations, we note that it is equivalent to

demand:

$$(1.3) \quad \int_{\Omega} \operatorname{curl} H \cdot \psi = \int_{\Omega} [-i\omega\varepsilon E + f_e] \cdot \psi$$

for every function  $\psi \in L^2(\Omega, \mathbb{C}^3)$  with support in some bounded set  $\Omega_R$ . In contrast to (1.2), the rotation in (1.3) does not act on the test-function; no boundary condition for  $H$  is explicitly encoded. Nevertheless, we will see below that the coupled system contains an implicit boundary condition for  $H$ .

The unknown  $E$  can be eliminated from the equations to obtain a single equation for the only unknown  $u := H$ . For an arbitrary function  $\phi \in H_{\text{cpt}}^1(\Omega)$ , we use  $\psi := \varepsilon^{-1} \operatorname{curl} \bar{\phi}$  in (1.3); the bar over a function denotes complex conjugation. Replacing the integral over  $E \cdot \operatorname{curl} \bar{\phi}$  with the help of (1.2), we obtain the following weak formulation of (1.1):

$$(1.4) \quad \int_{\Omega} \left\{ \frac{1}{\varepsilon} \operatorname{curl} u \cdot \operatorname{curl} \bar{\phi} - \omega^2 \mu u \bar{\phi} \right\} = \int_{\Omega} \left\{ \frac{1}{\varepsilon} f_e \operatorname{curl} \bar{\phi} - i\omega f_h \bar{\phi} \right\} \quad \forall \phi \in H_{\text{cpt}}^1(\Omega).$$

**1.3. Function spaces.** In the following, we will assume that  $f_e$  and  $f_h$  are vector fields with good decay properties, more precisely,

$$(1.5) \quad f_e, f_h \in L_*^2(\Omega, \mathbb{C}^3) := \left\{ f \in L^2(\Omega, \mathbb{C}^3) \mid \int_{\Omega} (1 + x_1^2)^2 |f(x)|^2 dx < \infty \right\}.$$

When we are interested in solutions to (1.4) with a decay for  $|x_1| \rightarrow \infty$ , we seek for

$$(1.6) \quad u \in H(\operatorname{curl}, \Omega) := \{ u \in L^2(\Omega, \mathbb{C}^3) \mid \operatorname{curl} u \in L^2(\Omega, \mathbb{C}^3) \},$$

and demand that (1.4) holds for all  $\phi$  in the same space. When we are interested in radiating solutions, we seek for  $u$  in the space

$$(1.7) \quad H_{\text{loc}}(\operatorname{curl}, \Omega) := \{ u : \Omega \rightarrow \mathbb{C} \mid \forall R > 0 : u|_{\Omega_R} \in H(\operatorname{curl}, \Omega_R) \},$$

where we used again  $\Omega_R = (-R, R) \times S$ . In this setting, we demand (1.4) for all  $\phi \in H(\operatorname{curl}, \Omega)$  with compact support in  $\bar{\Omega}$ . The remainder of this text is devoted to these two variants of the variational problem (1.4).

**1.4. Comments on the system.** The reader might be more familiar with the strong form of system (1.1), which reads

$$(1.8) \quad \operatorname{curl} \left( \frac{1}{\varepsilon} \operatorname{curl} H \right) - \omega^2 \mu H = \operatorname{curl} \left( \frac{1}{\varepsilon} f_e \right) - i\omega f_h.$$

We include a comment on the implied boundary conditions for  $H$ : Let us assume that the right hand side  $f_h$  is  $L^2$ -orthogonal to all gradients; this encodes  $\operatorname{div} f_h = 0$  and the boundary condition  $f_h \cdot \nu = 0$  on  $\partial\Omega$ . In this case, using a gradient  $\phi = \nabla\psi$  as test-function in (1.4), we find that also the function  $\mu u = \mu H$  is orthogonal to gradients. This encodes  $\operatorname{div}(\mu H) = 0$  in the domain and  $\mu H \cdot \nu = 0$  on the boundary. In particular: Solving the equations with  $f_h = 0$ , the solution satisfies automatically the boundary condition  $H \cdot \nu = 0$  on  $\partial\Omega$ .

On the equivalence of the two descriptions: We have shown that every solution of the original problem solves the variational problem (1.4). Vice versa, let  $H = u \in H_{\text{loc}}(\operatorname{curl}, \Omega)$  be a solution to (1.4). We define the electric field by  $E := i(\operatorname{curl} H - f_e)/(\omega\varepsilon)$  such that (1.3) is satisfied. We note that  $E \in L_{\text{loc}}^2(\Omega, \mathbb{C}^3)$  is satisfied and hence the definition of  $E$  together with (1.4) implies (1.2). Additionally, because of  $i\omega\mu H + f_h \in L_{\text{loc}}^2(\Omega, \mathbb{C}^3)$ , (1.2) also yields  $\operatorname{curl} E \in L_{\text{loc}}^2(\Omega, \mathbb{C}^3)$  and we conclude that (1.1) is also solved strongly, or, equivalently, pointwise almost everywhere.

It is often convenient to have the boundary condition for  $E$  encoded in the function space. With

$$H_0(\text{curl}, \Omega) := \left\{ u \in H(\text{curl}, \Omega) \mid \int_{\Omega} E \cdot \text{curl} \psi = \int_{\Omega} \text{curl} E \cdot \psi \quad \forall \psi \in H(\text{curl}, \Omega) \right\},$$

relation (1.2) is equivalent to:  $E$  satisfies  $E \in H_0(\text{curl}, \Omega)$  and the first equation of (1.1).

Our main results regard existence and uniqueness of solutions to (1.4). Our approach is quite similar to the one in [17], where we treated the Helmholtz equation. Since that article is quite detailed and contains proofs of all relevant tools (in particular Floquet-Bloch transformations and the fundamental functional analysis result), we focus here on those aspects of the analysis that are different for Maxwell's equations.

## 2. THE FLOQUET-BLOCH TRANSFORMED EQUATION

**2.1. Application of the Floquet-Bloch transform.** We use the Floquet-Bloch transformation in the  $x_1$ -variable. It transforms a function  $u = u(x)$ ,  $x \in \mathbb{R} \times S$  into a function  $\hat{u}$ . The transformed function has two arguments,  $\hat{u} = \hat{u}(x, \alpha)$ , where  $x$  ranges in the periodicity cell,  $x \in W := (0, 2\pi) \times S$ , and  $\alpha$  ranges in a unit interval,  $\alpha \in I := [-1/2, 1/2]$ . The two arguments are related by the fact that, for every  $\alpha \in I$ , the map  $W \ni x \mapsto \hat{u}(x, \alpha)$  is an  $\alpha$ -quasiperiodic function (the definition is given below).

The transformation is a bounded linear map

$$(2.1) \quad \mathcal{F}_{\text{FB}} : L^2(\Omega) \rightarrow L^2(W \times I), \quad u \mapsto \hat{u}.$$

For smooth functions  $u$  with compact support, writing  $x = (x_1, \tilde{x})$  for the argument, the transformation is defined by the formula

$$(2.2) \quad \hat{u}((x_1, \tilde{x}), \alpha) := \sum_{\ell \in \mathbb{Z}} u((x_1 + 2\pi\ell, \tilde{x})) e^{-i\ell 2\pi\alpha}.$$

The operator  $\mathcal{F}_{\text{FB}}$  is a unitary operator. We recall that [17] contains more details of the construction and proofs.

We have to introduce function spaces that are adapted to Maxwell's equations. We need spaces of periodic and of  $\alpha$ -quasiperiodic functions. In order to formulate periodicity on  $W$ , we start from

$$(2.3) \quad H_{\text{per,loc}}(\text{curl}, \Omega) := \{u : \Omega \rightarrow \mathbb{C} \mid u \text{ is } 2\pi\text{-periodic in } x_1, \\ \forall R > 0 : u|_{\Omega_R} \in H(\text{curl}, \Omega_R)\}.$$

This space allows to introduce periodic functions on  $W$ ,

$$(2.4) \quad H_{\text{per}}(\text{curl}, W) := \{u|_W \mid u \in H_{\text{per,loc}}(\text{curl}, \Omega)\},$$

and the space of  $\alpha$ -periodic functions

$$(2.5) \quad H_{\alpha}(\text{curl}, W) := \{u|_W \mid [x \mapsto u(x)e^{-i\alpha x_1}] \in H_{\text{per,loc}}(\text{curl}, \Omega)\}.$$

We equip the space  $H_{\alpha}(\text{curl}, W)$  with the inner product

$$(2.6) \quad \langle u, \phi \rangle_{H_{\alpha}(\text{curl}, W)} := \left\langle \frac{1}{\varepsilon} \text{curl} u, \text{curl} \phi \right\rangle_{L^2(W)} + \langle \mu u, \phi \rangle_{L^2(W)}.$$

The Floquet-Bloch transform is an isomorphism from  $H(\text{curl}, \Omega)$  to a space that we write as  $L^2(I, H_{\alpha}(\text{curl}, W))$ , elements of the latter are maps  $w : I \rightarrow H(\text{curl}, W)$  with  $w(\alpha) \in H_{\alpha}(\text{curl}, W)$  for almost every  $\alpha \in I$ .

For functions with decay, this allows an equivalent formulation of the variational problem. A function  $u \in H(\text{curl}, \Omega)$  solves (1.4) if, and only if, its transformation satisfies  $\hat{u} \in L^2(I, H_\alpha(\text{curl}, W))$  and

$$(2.7) \quad \int_W \left\{ \frac{1}{\varepsilon} \text{curl} \hat{u}(\cdot, \alpha) \cdot \text{curl} \bar{\phi} - \omega^2 \mu \hat{u}(\cdot, \alpha) \cdot \bar{\phi} \right\} \\ = \int_W \left\{ \frac{1}{\varepsilon} (\mathcal{F}_{\text{FB}} f_e)(\cdot, \alpha) \cdot \text{curl} \bar{\phi} - i\omega (\mathcal{F}_{\text{FB}} f_h)(\cdot, \alpha) \cdot \bar{\phi} \right\}$$

holds for every  $\phi \in H_\alpha(\text{curl}, W)$  and for almost every  $\alpha \in I$ . The proof is as that of Lemma 2.1 in [17]. Let us indicate the relevant calculation with the first term, where we use, in the first equality, the unitarity of  $\mathcal{F}_{\text{FB}}$  and, in the second equality, that multiplication with a  $2\pi$ -periodic function can be taken out of the Floquet-Bloch transformation (compare the definition in (2.2)), and that differential operators (such as curl) commute with the Floquet-Bloch transformation (here, we write  $\check{\phi}$  for the test function on  $\Omega$  and set  $\phi = \mathcal{F}_{\text{FB}}(\check{\phi})$ ):

$$\left\langle \frac{1}{\varepsilon} \text{curl} u, \text{curl} \check{\phi} \right\rangle_{L^2(\Omega)} = \int_I \langle \mathcal{F}_{\text{FB}}(\varepsilon^{-1} \text{curl} u)(\cdot, \alpha), \mathcal{F}_{\text{FB}}(\text{curl} \check{\phi})(\cdot, \alpha) \rangle_{L^2(W)} d\alpha \\ = \int_I \langle \varepsilon^{-1}(\cdot) \text{curl} \hat{u}(\cdot, \alpha), \text{curl} \phi(\cdot, \alpha) \rangle_{L^2(W)} d\alpha.$$

Since the test-function  $\phi(\cdot, \alpha)$  can be chosen arbitrarily, repeating the calculation for the other terms of (1.4), we arrive at (2.7) for almost every  $\alpha$ .

**2.2. Re-writing the equation with a family of operators.** We want to write the variational problem (2.7) with the help of operators. Since we want to construct operators that are defined on an  $\alpha$ -independent function space, we transform all equations to the space of periodic functions (which is the space corresponding to  $\alpha = 0$ ). We use  $X := H_{\text{per}}(\text{curl}, W)$  with the inner product of (2.6).

We note that a function  $x \mapsto U(x)$  is  $\alpha$ -periodic in  $x_1$  if, and only if, the function  $x \mapsto U(x)e^{-i\alpha x_1}$  is periodic in  $x_1$ . Instead of using  $\hat{u}(\cdot, \alpha) \in H_\alpha(\text{curl}, W)$  as an unknown, we seek for  $v(\cdot) := \hat{u}(\cdot, \alpha)e^{-i\alpha x_1} \in X$ .

For given  $v$ , the left hand side of (2.7) (with the replacements  $\hat{u}(\cdot, \alpha) = v(\cdot)e^{i\alpha x_1}$  and  $\phi(\cdot, \alpha) = \varphi(\cdot)e^{i\alpha x_1}$ ) defines an anti-linear form in  $\varphi$ , a map  $X \rightarrow \mathbb{C}$ . By the Riesz theorem on Hilbert spaces, this form can be represented by an element  $L_\alpha v$  via the scalar product in  $X$ . We obtain a bounded linear operator  $L_\alpha : X \rightarrow X$ , defined by the relation

$$(2.8) \quad \langle L_\alpha v, \varphi \rangle_X = \int_W \frac{1}{\varepsilon} \text{curl}(v e^{i\alpha x_1}) \cdot \text{curl}(\overline{\varphi e^{i\alpha x_1}}) - \omega^2 \mu v \cdot \bar{\varphi}$$

for all  $v, \varphi \in X$ . Accordingly, we represent the right hand side of (2.7) with an element  $y_\alpha \in X$ ,

$$(2.9) \quad \langle y_\alpha, \varphi \rangle_X = \int_W \left\{ \frac{1}{\varepsilon} (\mathcal{F}_{\text{FB}} f_e)(\cdot, \alpha) \cdot \text{curl}(\overline{\varphi e^{i\alpha x_1}}) - i\omega (\mathcal{F}_{\text{FB}} f_h)(\cdot, \alpha) \cdot \overline{\varphi e^{i\alpha x_1}} \right\}.$$

With these representations, the original problem (1.4) is solved when we find, for almost every  $\alpha \in I$ , a solution  $v(\cdot, \alpha) \in X$  of

$$(2.10) \quad L_\alpha v(\cdot, \alpha) = y_\alpha,$$

and if this family of solution satisfies  $v \in L^2(I, X)$ . This concludes the transformation of the equation, we arrived at a representation as in (2.14) of [17].

Since, for the existence result, we invert the order, let us outline the constructions of the next sections:

- Solve the abstract problem (2.10) for almost every  $\alpha \in I$ . This yields periodic functions  $v = v(\cdot, \alpha)$ . They are found with abstract functional analysis.
- Construct from  $v$  the  $\alpha$ -quasiperiodic counterparts  $\hat{u}(\cdot, \alpha)$ . By construction of (2.10), these counterparts solve (2.7).
- The (inverse) Floquet-Bloch transformation of  $\hat{u}(\cdot, \alpha)$  provides a solution  $u$  to (1.4). This was discussed above after (2.7).

Our next aim is to analyze the properties of the operator  $L_\alpha$ . Later on, the dependence on  $\alpha$  will be crucial. By contrast, in this section, we study, for a fixed  $\alpha \in I$ , the operator  $L_\alpha$ . The main result will be that  $L_\alpha$  is a self-adjoint Fredholm operator with index 0. We recall that  $\varepsilon$  and  $\mu$  are also fixed, real, and of class  $L^\infty(W)$  with a positive lower bound.

*Two equivalent operators.* The space of periodic functions is  $X$  and the operator on this space is  $L_\alpha$ . The space of  $\alpha$ -quasiperiodic functions is  $\tilde{X}_\alpha := H_\alpha(\text{curl}, W)$ , defined in (2.5). Every periodic function  $u \in X$  can be transformed to an  $\alpha$ -quasiperiodic function  $\tilde{u} \in \tilde{X}_\alpha$ , defined as  $\tilde{u}(x) := u(x)e^{i\alpha x_1}$ . This transformation defines an isomorphism between  $X$  and  $\tilde{X}_\alpha$ .

We must check the properties of the operator  $L_\alpha : X \rightarrow X$  of (2.8). For fixed  $\alpha$ , it is actually easier to perform proofs in the space of  $\alpha$ -quasiperiodic functions. Indeed, we recall that the operator  $L_\alpha$  was actually defined through the transformation of a problem in the space of  $\alpha$ -quasiperiodic functions, compare (2.7). The variational problem  $\langle L_\alpha u, \varphi \rangle_X = \int_W f \cdot \bar{\varphi}$  is identical to  $\langle \tilde{L}_\alpha \tilde{u}, \tilde{\varphi} \rangle_{\tilde{X}_\alpha} = \int_W \tilde{f} \cdot \bar{\tilde{\varphi}}$  with the functions  $\tilde{u}(x) = u(x)e^{i\alpha x_1}$  and  $\tilde{f}(x) = f(x)e^{i\alpha x_1}$  for the operator  $\tilde{L}_\alpha : \tilde{X}_\alpha \rightarrow \tilde{X}_\alpha$  defined by

$$(2.11) \quad \langle \tilde{L}_\alpha \tilde{u}, \tilde{\varphi} \rangle_{\tilde{X}_\alpha} = \int_W \frac{1}{\varepsilon} \text{curl } \tilde{u} \cdot \text{curl } \bar{\tilde{\varphi}} - \omega^2 \mu \tilde{u} \cdot \bar{\tilde{\varphi}}$$

for all  $\tilde{u}, \tilde{\varphi} \in \tilde{X}_\alpha$ .

We claim that the operator  $L_\alpha$  is a Fredholm operator if, and only if,  $\tilde{L}_\alpha$  is Fredholm, and that the index of the two operators coincides. Indeed, when the kernel of  $L_\alpha$  is spanned by  $u_1, \dots, u_M$ , then the transformed functions defined as  $\tilde{u}_m(x) := u_m(x)e^{i\alpha x_1}$  span the kernel of  $\tilde{L}_\alpha$ , and vice versa. Similarly, when  $u_1, \dots, u_M$  span a complement of  $L_\alpha(X)$ , then the transformed functions span a complement of  $\tilde{L}_\alpha(\tilde{X}_\alpha)$ .

In Lemma B.1 of Appendix B we prove that  $\tilde{L}_\alpha$  of (2.11) is a Fredholm operator with index 0. This implies the following result.

**Proposition 2.1** (Properties of  $L_\alpha$ ). *Let  $\varepsilon, \mu : \Omega \rightarrow \mathbb{R}$  be as described after (1.1). For  $\alpha \in I = [-1/2, 1/2]$  we consider, on the space  $X = H_{\text{per}}(\text{curl}, W)$ , the operator  $L_\alpha : X \rightarrow X$  of (2.8). Then  $L_\alpha$  is a self-adjoint Fredholm operator with index 0.*

### 3. EXISTENCE OF SOLUTIONS TO THE MAXWELL RADIATION PROBLEM

From now on and until the start of Subsection 3.6, we consider the homogeneous equations, i.e.,  $(f_e, f_h) = 0$ . We recall that  $\varepsilon$  and  $\mu$  are real and have a positive lower bound.

**3.1. Physical conservation laws: Poynting vector and energy flux.** For a solution  $(E, H)$  of the Maxwell system, the Poynting vector  $P := \frac{1}{2} E \times \bar{H}$  describes the flow of energy. More precisely, through a cross-section  $\Gamma_r := \{r\} \times S$  of the waveguide with normal vector  $e_1 = (1, 0, 0) \in \mathbb{R}^3$ , the quantity  $\frac{1}{2} \text{Re} \int_{\Gamma_r} (E \times \bar{H}) \cdot e_1$



is the energy flux through  $\Gamma_r$ . This motivates to study, for a position  $r \in \mathbb{R}$  and a solution  $H$ , the real valued flux quantity

$$(3.1) \quad \mathcal{F}_r := -2 \operatorname{Im} \int_{\Gamma_r} \frac{1}{\varepsilon} (\operatorname{curl} H \times \bar{H}) \cdot e_1.$$

Conservation of energy is reflected by the fact that the flux  $\mathcal{F}_r$  is independent of the position  $r$ .

Let us sketch the argument for smooth coefficients  $\mu$  and  $\varepsilon$  and a classical solution  $H$  of the Maxwell system (1.4) (below, we provide rigorous derivations for weak solutions): For two positions  $-\infty < s < r < \infty$  and the domain  $\Omega_{s,r} := (s, r) \times S$  with characteristic function  $\chi$  we use the test-function  $\phi = u \chi$  in (1.4). The right hand side vanishes, on the left, we integrate by parts and take the imaginary part. The bulk term is real because of the strong equation  $\operatorname{curl}(\varepsilon^{-1} \operatorname{curl} H) - \omega^2 \mu H = 0$ , hence the imaginary part of the bulk term vanishes. There remain only boundary terms, they coincide with the expression in (3.1). We find that the expression  $\mathcal{F}_r$  is independent of  $r$ .

Our next aim is to prove this fact in a generalized setting for weak solutions.

**3.2. Generalization and weak description.** We consider two weak solutions  $u$  and  $v$  to the homogeneous problem, i.e., both  $u$  and  $v$  solve

$$(3.2) \quad \int_{\Omega} \left\{ \frac{1}{\varepsilon} \operatorname{curl} u \cdot \operatorname{curl} \bar{\phi} - \omega^2 \mu u \bar{\phi} \right\} = 0 \quad \text{for every } \phi \in H_{\text{cpt}}^1(\Omega).$$

We consider an arbitrary weight function,  $\eta : \mathbb{R} \rightarrow \mathbb{R}$  bounded with compact support and with  $\int_{\mathbb{R}} \eta = 1$ . We interpret  $\eta$  also as a function on  $\Omega$  by setting  $\eta(x) := \eta(x_1)$ . We introduce the weighted average of the complex flux,

$$(3.3) \quad \mathcal{F}_{u,v} := i \int_{\Omega} \eta \frac{1}{\varepsilon} [(\operatorname{curl} u \times \bar{v}) - (\operatorname{curl} \bar{v} \times u)] \cdot e_1.$$

Conservation of energy is now reflected by the fact that the expression  $\mathcal{F}_{u,v}$  is independent of the weight  $\eta$ . Indeed, when  $\eta_1$  and  $\eta_2$  are two weight functions as above, we use the primitive of the difference,  $\vartheta(t) := \int_{-\infty}^t (\eta_1 - \eta_2)(s) ds$ , a Lipschitz function with compact support. Once more, we interpret  $\vartheta$  also as a function on  $\Omega$ .

We use  $\phi = v \vartheta$  as a test-function for the solution  $u$  of (3.2). We then use  $\phi = u \vartheta$  as a test-function for the solution  $v$  and take the complex conjugate of the result. When subtracting the two expressions, terms without derivatives of  $\vartheta$  cancel. There remain only terms that contain a derivative of  $\vartheta(x)$ , which is  $\nabla \vartheta(x) = (\eta_1 - \eta_2)(x) e_1$ . The result is that, indeed, the expression of (3.3), is independent of  $\eta$ .

Motivated by this calculation, we introduce two sesquilinear forms on functions  $u, \phi \in H(\operatorname{curl}, W)$  for  $W = (0, 2\pi) \times S$ :

$$(3.4) \quad Q(u, \phi) := i \int_W \frac{1}{\varepsilon} [(\operatorname{curl} u \times \bar{\phi}) - (\operatorname{curl} \bar{\phi} \times u)] \cdot e_1.$$

The form  $Q$  is hermitean, since  $\varepsilon$  is real. We emphasize that the arguments of  $Q$  are not necessarily periodic functions; indeed, we will typically use  $\alpha$ -quasiperiodic functions as arguments. Solutions  $u, v$  of (3.2) satisfy

$$(3.5) \quad Q(u, v) = 2\pi \mathcal{F}_{u,v}.$$

**3.3. Non-degeneracy of  $Q$ .** We will always make the following physically meaningful assumption. We recall that, for  $\alpha \in I = [-1/2, 1/2]$ , the operator  $L_\alpha : X \rightarrow X$  on  $X = H_{\text{per}}(\operatorname{curl}, W)$  was defined in (2.8).

**Assumption 3.1** (Energy transport of quasiperiodic solutions). *We introduce the set of critical  $\alpha$ -values*

$$(3.6) \quad \mathcal{A} := \{\alpha \in (-1/2, 1/2] \mid \ker(L_\alpha) \neq \{0\}\}.$$

*We assume that, for every  $\alpha \in \mathcal{A}$  and for every  $0 \neq v \in \ker(L_\alpha)$ , the linear form  $Q(\cdot, v)$  does not vanish identically on  $\ker(L_\alpha)$ .*

The assumption demands, loosely speaking, that there is no quasiperiodic homogeneous solution to the Maxwell equation that is not transporting energy.

We note that the operators  $L_\alpha$  coincide for  $\alpha = 1/2$  and  $\alpha = -1/2$ . We therefore do not consider the value  $\alpha = -1/2$  in the set  $\mathcal{A}$ .

**3.4. The derivative of  $L_\alpha$ .** For the space  $X = H_{\text{per}}(\text{curl}, W)$  and  $L_\alpha : X \rightarrow X$  of (2.8), we now compute the derivative of  $L_\alpha$  with respect to  $\alpha$ .

**Lemma 3.2** (Derivative of  $L_\alpha$ ). *The derivative  $\partial_\alpha L_\alpha : X \rightarrow X$  is given by  $Q$  in the sense that*

$$(3.7) \quad \langle \partial_\alpha L_\alpha v, \varphi \rangle_X = Q(v e^{i\alpha x_1}, \varphi e^{i\alpha x_1})$$

*for every  $v, \varphi \in X$ . In particular, when Assumption 3.1 holds, the derivative  $\partial_\alpha L_\alpha$  is non-degenerate on the kernel of  $L_\alpha$  for every  $\alpha \in \mathcal{A}$ .*

*Proof.* For arbitrary  $v, \varphi \in X$  we can calculate

$$\begin{aligned} \langle \partial_\alpha L_\alpha v, \varphi \rangle_X &= \partial_\alpha \langle L_\alpha v, \varphi \rangle_X \\ &= \partial_\alpha \int_W \frac{1}{\varepsilon} \text{curl}(v e^{i\alpha x_1}) \cdot \text{curl}(\overline{\varphi e^{i\alpha x_1}}) - \omega^2 \mu v \cdot \bar{\varphi} \\ &= i \int_W \frac{1}{\varepsilon} \left\{ \text{curl}(v x_1 e^{i\alpha x_1}) \cdot \text{curl}(\overline{\varphi e^{i\alpha x_1}}) - \text{curl}(v e^{i\alpha x_1}) \cdot \text{curl}(\overline{\varphi x_1 e^{i\alpha x_1}}) \right\} \\ &= i \int_W \frac{1}{\varepsilon} \left\{ (e_1 \times v e^{i\alpha x_1}) \cdot \text{curl}(\overline{\varphi e^{i\alpha x_1}}) - (e_1 \times \overline{\varphi e^{i\alpha x_1}}) \cdot \text{curl}(v e^{i\alpha x_1}) \right\} \\ &= Q(v e^{i\alpha x_1}, \varphi e^{i\alpha x_1}). \end{aligned}$$

This provides (3.7). □

**3.5. Functional analysis.** When Assumption 3.1 is satisfied, Proposition 2.1 provides a Fredholm property of the family  $(L_\alpha)_\alpha$ , and Lemma 3.2 implies the non-degeneracy of the  $\alpha$ -derivatives. These properties imply that the family  $(L_\alpha)_\alpha$  is a *regular  $C^1$ -family of operators* in the sense of Definition 3.1 of [17]. For regular  $C^1$ -families of operators, the subsequent result was shown in [17]. We use the same notation, with only one minimal change: We have to replace the variable  $\varepsilon > 0$  by  $\delta > 0$ , because in Maxwell's equations  $\varepsilon$  is the name of the permittivity. We use  $I_\delta := (-1/2 - \delta, 1/2 + \delta)$ ,  $\mathcal{N} := \ker(L_\alpha)$ ,  $\mathcal{R} := L_\alpha(X) \subset X$ , and the projection  $P$  onto  $\mathcal{N}$  corresponding to  $X = \mathcal{N} \oplus \mathcal{R}$ . Theorem 3.2 of [17] provides:

**Theorem 3.3** (Functional analysis). *Let Assumption 3.1 hold. The family  $L_\alpha$  has the following properties.*

1. *The set of critical numbers is finite: For a number  $J \in \mathbb{N}$  (we allow  $J = 0$  for an empty set  $\mathcal{A}$ ) and values  $\{\alpha_j \mid 0 < j \leq J\}$  holds*

$$(3.8) \quad \mathcal{A} := \{\alpha \in (-1/2, 1/2] \mid \ker(L_\alpha) \neq \{0\}\} = \{\alpha_j \mid 0 < j \leq J\}.$$

2. For some  $\delta > 0$ , let  $I_\delta \ni \alpha \mapsto y_\alpha$  be a  $C^1$ -family of right hand sides with the property that  $y_\alpha \in L_\alpha(X)$  holds for every  $\alpha \in I_\delta$  with  $\ker(L_\alpha) \neq \{0\}$ . Then the family of solutions

$$I_\delta \setminus \mathcal{A} \ni \alpha \mapsto u_\alpha := (L_\alpha)^{-1}(y_\alpha)$$

can be continued to a  $C^0$ -family on  $I_\delta$ . For some constant  $C > 0$ , which is independent of the family  $(y_\alpha)_\alpha$ , there holds, with the derivative  $y' = \partial_\alpha y$ ,

$$(3.9) \quad \sup_{\alpha \in I} \|u_\alpha\|_X \leq C \sup_{\alpha \in I} [\|y_\alpha\|_X + \|y'_\alpha\|_X].$$

The theorem implies that there exists a finite number of quasimoments  $(\alpha_j)_{1 \leq j \leq J}$ , corresponding to propagative wave numbers. They are characterized by the fact that the kernel  $\ker(L_{\alpha_j}) = \{\varphi \mid L_{\alpha_j}\varphi = 0\}$  is not trivial. The kernels are finite dimensional. We introduce, for every  $0 < j \leq J$ , the space of  $\alpha_j$ -quasiperiodic propagating modes

$$(3.10) \quad Y_j := \{\phi \in H_{\alpha_j}(\text{curl}, \Omega) \mid \phi \text{ satisfies (1.4) for } f_h = f_e = 0\}.$$

There holds  $\ker(L_{\alpha_j}) = \{\phi e^{-i\alpha_j x_1} \mid \phi \in Y_j\}$ , we denote the dimension by  $m_j := \dim Y_j = \dim \ker(L_{\alpha_j})$ . In every space  $Y_j$  we choose a basis  $\{\phi_{1,j}, \dots, \phi_{m_j,j}\} \subset Y_j$  as follows: We fix an inner product  $\langle \cdot, \cdot \rangle_{Y_j}$  and consider the self-adjoint eigenvalue problem to find  $\lambda \in \mathbb{R}$  and  $0 \neq \phi \in Y_j$  such that

$$Q(\phi, \cdot) = \lambda \langle \phi, \cdot \rangle_{Y_j}.$$

We denote the eigenvalues by  $\lambda_{\ell,j}$ ,  $\ell = 1, \dots, m_j$ , and the eigenfunctions by  $\phi_{\ell,j}$ ,  $\ell = 1, \dots, m_j$ , normalized such that

$$\langle \phi_{\ell,j}, \phi_{\ell',j} \rangle_{Y_j} = \delta_{\ell,\ell'}, \quad \ell, \ell' = 1, \dots, m_j.$$

The following lemma translates Lemma 3.4 of [17] to the Maxwell system. We recall the short and simple proof.

**Lemma 3.4** (Orthogonality). *The spaces  $Y_j$  are orthogonal with respect to the form  $Q$ : There holds  $Q(u, v) = 0$  for  $u \in Y_j$  and  $v \in Y_{j'}$  whenever  $j \neq j'$ .*

*Proof.* We evaluate the expression  $\mathcal{F}_{u,v}$  of (3.3) for two weights  $\eta_1(\cdot) = \eta(\cdot)$  and  $\eta_2(\cdot) = \eta(\cdot + 2\pi e_1)$ . We evaluate  $\mathcal{F}_{u,v}$  with the weight  $\eta_2$  by a substitution, using that  $u$  is  $\alpha_j$  quasiperiodic and  $v$  is  $\alpha_{j'}$  quasiperiodic. The fact that  $\mathcal{F}_{u,v}$  is independent of the weight  $\eta$  implies  $\mathcal{F}_{u,v} = e^{2\pi i \alpha_j} e^{-2\pi i \alpha_{j'}} \mathcal{F}_{u,v}$ . This implies  $\mathcal{F}_{u,v} = 0$  and thus  $Q(u, v) = 0$ .  $\square$

We re-arrange the basis functions into the set  $\{\phi_\ell \mid \ell = 1, \dots, L\}$  where  $L := \sum_{j \in J} m_j$ . With the corresponding eigenvalues  $\lambda_\ell$  we can formulate: Assumption 3.1 is satisfied if, and only if,  $Q(\phi_\ell, \phi_\ell) = \lambda_\ell \neq 0$  for all  $\ell = 1, \dots, L$ .

**3.6. Solutions with decay**,  $u \in H(\text{curl}, \Omega)$ . We can now formulate the existence and uniqueness result in  $H(\text{curl}, \Omega)$ . This result gives the unique existence of a decaying solution for right hand sides that satisfy an orthogonality condition.

**Theorem 3.5** (Existence and uniqueness of  $H(\text{curl}, \Omega)$ -solutions). *Let  $S$ ,  $\varepsilon$ ,  $\mu$ ,  $\omega$  be as described after (1.1) and let Assumption 3.1 hold. We assume that the right hand side functions  $f_e, f_h \in L_*^2(\Omega, \mathbb{C}^3)$  are orthogonal to the propagating modes  $(\phi_\ell)_\ell$  in the following sense:*

$$(3.11) \quad \int_{\Omega} \frac{1}{\varepsilon} f_e \cdot \text{curl} \overline{\phi_\ell} - i\omega f_h \overline{\phi_\ell} = 0 \quad \text{for every } \ell = 1, \dots, L.$$

*Then there exists a unique solution  $u \in H(\text{curl}, \Omega)$  of (1.4). There exists a constant  $C > 0$ , independent of  $f_e$  and  $f_h$ , such that  $\|u\|_{H(\text{curl}, \Omega)} \leq C (\|f_e\|_{L_*^2(\Omega)} + \|f_h\|_{L_*^2(\Omega)})$ .*

*Proof. Step 1: Solvability.* We use  $L_\alpha$  of (2.8) and  $y_\alpha$  of (2.9). We solve, for  $\alpha \in I$ , the family of equations  $L_\alpha v(\cdot, \alpha) = y_\alpha$  of (2.10). This is done with Theorem 3.3, Part 2., the only point that we have to verify is  $y_\alpha \in L_\alpha(X)$ . Once this is checked, estimate (3.9) yields also that the solutions satisfy  $v \in L^2(I, X)$ , even  $v \in L^\infty(I, X)$ .

For fixed  $j \leq J$  and fixed  $\ell \leq m_j$ , we consider the basis function  $\varphi_{\ell,j} \in \ker(L_{\alpha_j})$  and the  $\alpha_j$ -quasiperiodic function  $\phi_{\ell,j}(x) := \varphi_{\ell,j}(x)e^{i\alpha_j x_1} \in Y_j$ . For notational convenience, we perform the calculations for the case  $f_h = 0$ . Starting with the orthogonality information (3.11), we find

$$\begin{aligned} 0 &= \int_{\Omega} \frac{1}{\varepsilon} f_e \cdot \operatorname{curl} \overline{\phi_{\ell,j}} \\ &= \sum_{m \in \mathbb{Z}} \int_W \varepsilon(x)^{-1} f_e(x + 2\pi m e_1) \operatorname{curl} \overline{\phi_{\ell,j}(x + 2\pi m e_1)} dx \\ &= \sum_{m \in \mathbb{Z}} \int_W \varepsilon(x)^{-1} f_e(x + 2\pi m e_1) e^{-i2\pi\alpha_j m} \operatorname{curl} \overline{\phi_{\ell,j}(x)} dx \\ &= \int_W \varepsilon(x)^{-1} (\mathcal{F}_{\text{FB}} f_e)(x, \alpha_j) \operatorname{curl} \overline{\phi_{\ell,j}(x)} dx \\ &= \langle y_{\alpha_j}, \varphi_{\ell,j} \rangle_X, \end{aligned}$$

where the last step uses the definition of  $y_{\alpha_j}$ . The calculation provides that  $y_{\alpha_j}$  is orthogonal to the kernel of  $L_{\alpha_j}$ . Since  $L_{\alpha_j}$  is a self-adjoint Fredholm operator with index 0 by Proposition 2.1, we conclude that  $y_{\alpha_j}$  is in the range of  $L_{\alpha_j}$  (kernel and range are orthogonal for self-adjoint operators, the vanishing index implies that kernel and range span the entire space). This yields  $y_\alpha \in L_\alpha(X)$ .

The result  $y_\alpha \in L_\alpha(X)$  for  $\alpha = 1/2$  implies the same result for  $\alpha = -1/2$ , because the operators  $L_\alpha$  and the right hand sides  $y_\alpha$  coincide. The calculations for  $f_h \neq 0$  are completely analogous.

*Step 2: Bounds on the solution.* Theorem 3.3 implies a bound (uniform in  $\alpha$ ) for  $v_\alpha := v(\cdot, \alpha)$ , namely  $\sup_\alpha \|v_\alpha\|_X \leq C \sup_\alpha [\|y_\alpha\|_X + \|y'_\alpha\|_X]$ . We note that

$$\begin{aligned} \|y_\alpha\|_X &= \sup \{ \langle y_\alpha, \phi \rangle_X \mid \|\phi\|_X = 1 \} \\ &\leq C \left( \|(\mathcal{F}_{\text{FB}} f_e)(\cdot, \alpha)\|_{L^2(W)} + \|(\mathcal{F}_{\text{FB}} f_h)(\cdot, \alpha)\|_{L^2(W)} \right) \end{aligned}$$

and

$$\begin{aligned} \|y'_\alpha\|_X &= \sup \left\{ \frac{d}{d\alpha} \langle y_\alpha, \phi \rangle_X \mid \|\phi\|_X = 1 \right\} \\ &\leq C \sum_{\# \in \{e, h\}} \left( \|(\mathcal{F}_{\text{FB}} f_{\#})(\cdot, \alpha)\|_{L^2(W)} + \left\| \frac{\partial}{\partial \alpha} (\mathcal{F}_{\text{FB}} f_{\#})(\cdot, \alpha) \right\|_{L^2(W)} \right). \end{aligned}$$

As in [17], Theorem 3.8, these terms can be estimated by  $\sum_{\# \in \{e, h\}} \|f_{\#}\|_{L^2_*(\Omega)}$ ; the argument for this fact exploits that good decay properties of  $f_{\#}$  imply good regularity properties of  $\mathcal{F}_{\text{FB}} f_{\#}$ . We can therefore define  $u$  by the inverse Floquet-Bloch transform,

$$u(x + 2\pi \ell e_1) := \int_I v(x, \alpha) e^{i(x_1 + 2\pi \ell)\alpha} d\alpha, \quad x \in W, \ell \in \mathbb{Z}.$$

As discussed above,  $u \in H(\operatorname{curl}, \Omega)$  is a solution of (1.4). Furthermore, since  $\mathcal{F}_{\text{FB}}$  is an isometry,

$$\|u\|_{H(\operatorname{curl}, \Omega)}^2 = \|v\|_{L^2(I, X)}^2 \leq \sup_\alpha \|v(\cdot, \alpha)\|_X^2 \leq C \left( \|f_e\|_{L^2_*(\Omega)}^2 + \|f_h\|_{L^2_*(\Omega)}^2 \right).$$

This provides the a priori estimate.  $\square$

**3.7. The radiation problem.** In order to formulate the radiation problem, we introduce cut-off functions  $\rho_+$  and  $\rho_-$ .

**Definition 3.6** (Cut-off functions  $\rho_\pm$ ). *We say that  $\rho_+, \rho_- : \mathbb{R} \rightarrow \mathbb{R}$  are admissible cut-off functions when they are Lipschitz-continuous, satisfy  $\rho_\pm(x_1) \in [0, 1]$  for every  $x_1 \in \mathbb{R}$ , and the limiting behavior is*

$$\begin{aligned} \rho_+(x_1) &\rightarrow 1 \text{ for } x_1 \rightarrow \infty, & \rho_+(x_1) &\rightarrow 0 \text{ for } x_1 \rightarrow -\infty, \\ \rho_-(x_1) &\rightarrow 0 \text{ for } x_1 \rightarrow \infty, & \rho_-(x_1) &\rightarrow 1 \text{ for } x_1 \rightarrow -\infty. \end{aligned}$$

Moreover, we demand specific decay properties:  $1 - \rho_+ \in L^2(\mathbb{R}_{>0})$  and  $\rho_+ \in L^2(\mathbb{R}_{<0})$ , and, analogously,  $1 - \rho_- \in L^2(\mathbb{R}_{<0})$  and  $\rho_- \in L^2(\mathbb{R}_{>0})$ . Additionally, for the derivative, we demand  $\partial_{x_1} \rho_\pm \in L^2(\mathbb{R})$ .

We fix admissible cut-off functions  $\rho_\pm$  as in Definition 3.6. For every  $\ell \leq L$  the mode  $\phi_\ell$  is called right-going when  $Q(\phi_\ell, \phi_\ell) > 0$ , it is called left-going when  $Q(\phi_\ell, \phi_\ell) < 0$ . Note that, when  $Q$  is non-degenerate, these are the only possible cases. For every  $\ell$  such that  $\phi_\ell$  is right-going, we set  $\rho_\ell := \rho_+$ , and for every  $\ell$  for which  $\phi_\ell$  is left-going, we set  $\rho_\ell := \rho_-$ .

**Definition 3.7** (Propagating part and radiation condition). *For fixed cut-off functions  $\rho_\ell$  as above, we introduce the following decomposition of solutions  $u$ .*

(i) Propagating part. *For complex coefficients  $(a_\ell)_{1 \leq \ell \leq L}$ , we say that*

$$(3.12) \quad u^{\text{prop}} := \sum_{\ell=1}^L a_\ell \rho_\ell \phi_\ell$$

is the propagating wave function corresponding to  $a \in \mathbb{C}^L$ .

(ii) Radiation condition. *We say that a solution  $u \in H_{\text{loc}}(\text{curl}, \Omega)$  of (1.4) satisfies the radiation condition, when there exists  $a \in \mathbb{C}^L$  such that, with the corresponding propagating wave function  $u^{\text{prop}}$  of (3.12), there holds*

$$(3.13) \quad u^{\text{rad}} := u - u^{\text{prop}} \in H(\text{curl}, \Omega).$$

**Remark 3.8.** *The radiation condition was formulated for given functions  $\rho_\pm$ . We remark that, when  $\rho_\pm$  is replaced by another admissible pair  $\tilde{\rho}_\pm$ , the coefficients  $(a_\ell)_\ell$  remain unchanged. Indeed, this follows from  $\sum_{\ell=1}^L a_\ell (\rho_\ell - \tilde{\rho}_\ell) \phi_\ell \in H(\text{curl}, \Omega)$ . In particular, we can choose  $\rho_\pm$  such that  $\rho_\pm(x_1) = 1$  for  $\pm x_1 > R$  and  $\rho_\pm(x_1) = 0$  for  $\pm x_1 < -R$  for some  $R > 0$ .*

**Theorem 3.9** (Existence and uniqueness of solutions to the radiation problem). *Let  $S, \omega, \varepsilon, \mu$  be as described after (1.1) and let  $f_e$  and  $f_h$  be as in (1.5). Let Assumption 3.1 be satisfied and let admissible cut-off functions  $(\rho_\ell)_\ell$  be chosen as in Definition 3.6. Then (1.4) has a unique solution  $u \in H_{\text{loc}}(\text{curl}, \Omega)$  satisfying the radiation condition of Definition 3.7. With  $u^{\text{prop}}, u^{\text{rad}}$ , and  $a$  from the radiation condition and a constant  $C = C(S, \varepsilon, \mu, \omega, \rho_\pm)$ , there holds*

$$(3.14) \quad \|u^{\text{rad}}\|_{H(\text{curl}, \Omega)} + \|u^{\text{prop}}\|_W + \|a\|_{\mathbb{C}^L} \leq C (\|f_e\|_{L^2_*(\Omega)} + \|f_h\|_{L^2_*(\Omega)}).$$

The coefficients  $(a_\ell)_{1 \leq \ell \leq L}$  are given by

$$(3.15) \quad a_\ell = \frac{2\pi i}{|Q(\phi_\ell, \phi_\ell)|} (\langle \varepsilon^{-1} f_e, \text{curl} \phi_\ell \rangle_{L^2(\Omega)} - \langle i\omega f_h, \phi_\ell \rangle_{L^2(\Omega)}).$$

*Proof.* The strategy of the proof is very direct: We want to apply Theorem 3.5 to find  $u^{\text{rad}}$  as described in the radiation problem. In order to apply Theorem 3.5, we must make sure that the right hand side of the  $u^{\text{rad}}$ -problem satisfies the

orthogonality condition (3.11). As mentioned in Remark 3.8, we can assume that the cut-off functions  $\rho_{\pm}$  are chosen such that they are constant outside of some bounded interval, i.e., the functions  $\rho'_\ell$  have compact support.

We want to find coefficients  $a = (a_\ell)_\ell$ , such that, with  $u^{\text{prop}}$  defined by  $a$ , the equation for  $u^{\text{rad}}$  has a right hand side that satisfies the orthogonality condition. We will see that the coefficients  $a$  of (3.15) have this property.

*Step 1: Equation for  $u^{\text{rad}}$ .* We derive, for fixed coefficients  $(a_\ell)_\ell$ , the equation for  $u^{\text{rad}}$ . Starting from (1.4), using  $u = u^{\text{rad}} + u^{\text{prop}}$  and  $u^{\text{prop}} = \sum_{\ell=1}^L a_\ell \rho_\ell \phi_\ell$ , we find that  $u^{\text{rad}}$  should satisfy, for every  $\bar{\phi}$  with compact support,

$$\begin{aligned} & \int_{\Omega} \left\{ \frac{1}{\varepsilon} \operatorname{curl} u^{\text{rad}} \cdot \operatorname{curl} \bar{\phi} - \omega^2 \mu u^{\text{rad}} \cdot \bar{\phi} \right\} \\ &= - \sum_{\ell=1}^L a_\ell \int_{\Omega} \left\{ \frac{1}{\varepsilon} \operatorname{curl}(\rho_\ell \phi_\ell) \cdot \operatorname{curl} \bar{\phi} - \omega^2 \mu \rho_\ell \phi_\ell \cdot \bar{\phi} \right\} \\ & \quad + \int_{\Omega} \left\{ \frac{1}{\varepsilon} f_e \cdot \operatorname{curl} \bar{\phi} - i\omega f_h \cdot \bar{\phi} \right\}. \end{aligned}$$

The next step is to re-write the terms in the first integral on the right hand side. Our aim is to exploit the homogeneous equation which is satisfied by  $\phi_\ell$ . With this aim, we calculate

$$\begin{aligned} \int_{\Omega} \frac{1}{\varepsilon} \operatorname{curl}(\rho_\ell \phi_\ell) \cdot \operatorname{curl} \bar{\phi} &= \int_{\Omega} \frac{1}{\varepsilon} \rho_\ell \operatorname{curl} \phi_\ell \cdot \operatorname{curl} \bar{\phi} + \int_{\Omega} \frac{1}{\varepsilon} \rho'_\ell (e_1 \times \phi_\ell) \cdot \operatorname{curl} \bar{\phi} \\ &= \int_{\Omega} \frac{1}{\varepsilon} \operatorname{curl} \phi_\ell \cdot \operatorname{curl}(\rho_\ell \bar{\phi}) + \int_{\Omega} \frac{1}{\varepsilon} \rho'_\ell e_1 \cdot [\phi_\ell \times \operatorname{curl} \bar{\phi} - \bar{\phi} \times \operatorname{curl} \phi_\ell]. \end{aligned}$$

In this expression, we can exploit that  $\phi_\ell$  solves (1.4) with vanishing right hand side; the test function is the compactly supported function  $\rho_\ell \phi$ . This leads to the cancelling of lower order terms and we arrive at the following equation for  $u^{\text{rad}}$ :

$$\begin{aligned} & \int_{\Omega} \left\{ \frac{1}{\varepsilon} \operatorname{curl} u^{\text{rad}} \cdot \operatorname{curl} \bar{\phi} - \omega^2 \mu u^{\text{rad}} \cdot \bar{\phi} \right\} \\ (3.16) \quad &= - \sum_{\ell=1}^L a_\ell \int_{\Omega} \frac{1}{\varepsilon} \rho'_\ell e_1 \cdot [\phi_\ell \times \operatorname{curl} \bar{\phi} - \bar{\phi} \times \operatorname{curl} \phi_\ell] \\ & \quad + \int_{\Omega} \left\{ \frac{1}{\varepsilon} f_e \cdot \operatorname{curl} \bar{\phi} - i\omega f_h \cdot \bar{\phi} \right\}. \end{aligned}$$

We note that the terms containing  $\rho'_\ell$  are compactly supported, accordingly, the right hand side of this equation has the property of fast decay that is required in Theorem 3.5.<sup>1</sup>

*Step 2: Orthogonality condition.* It remains to choose  $(a_\ell)_\ell$  such that the orthogonality condition is satisfied. We use, for arbitrary  $k \leq L$ , the test function  $\bar{\phi} := \phi_k$  in (3.16). The integrals containing  $\rho'_\ell$  are equal to

$$\begin{aligned} \int_{\Omega} \frac{1}{\varepsilon} \rho'_\ell e_1 \cdot [\phi_\ell \times \operatorname{curl} \bar{\phi}_k - \bar{\phi}_k \times \operatorname{curl} \phi_\ell] &= -i \mathcal{F}_{\phi_\ell, \phi_k} \operatorname{sign} \int_{\mathbb{R}} \rho'_\ell(x_1) dx_1 \\ &= -\frac{i}{2\pi} |Q(\phi_\ell, \phi_k)|, \end{aligned}$$

<sup>1</sup>The right hand side in the equation for  $u^{\text{rad}}$  contains the curl of the test-function, but it also contains the test-function itself. This is the technical reason why we included the right hand side  $f_h$  in the original system.

where we used (3.5) and  $\int_{\mathbb{R}} \rho'_\ell = \text{sign}(Q(\phi_\ell, \phi_\ell))$ . The right hand side of (3.16) for  $\phi := \phi_k$  is therefore

$$\sum_{\ell=1}^L a_\ell \frac{i}{2\pi} |Q(\phi_\ell, \phi_k)| + \int_{\Omega} \left\{ \frac{1}{\varepsilon} f_e \cdot \text{curl} \bar{\phi}_k - i\omega f_h \cdot \bar{\phi}_k \right\}.$$

Using finally  $|Q(\phi_\ell, \phi_k)| = |Q(\phi_k, \phi_k)| \delta_{k,\ell}$ , we conclude that, with  $(a_\ell)_\ell$  chosen as in (3.15), the right hand side of (3.16) vanishes for every  $\phi := \phi_k$ . We can apply Theorem 3.5 to find  $u^{\text{rad}}$ . This yields a solution of the Maxwell radiation problem together with the estimates of (3.14).  $\square$

#### 4. TWO SPACES OF HOMOGENEOUS SOLUTIONS

*The space  $Y$ .* Let us first recall the spaces that were used in the above constructions, based on Assumption 3.1. The space  $Y_j$  of (3.10) consists of  $\alpha_j$ -quasiperiodic homogeneous solutions, we recall  $\alpha_j \in (-1/2, 1/2]$ . When we take the span of all the Floquet-modes, we obtain the space

$$(4.1) \quad Y := \bigoplus_{j=1}^J Y_j \subset H(\text{curl}, W), \quad \text{identified with } Y \subset H_{\text{loc}}(\text{curl}, \Omega).$$

The identification is done by considering every  $\alpha_j$ -quasiperiodic function on  $W$  also as an  $\alpha_j$ -quasiperiodic function on  $\Omega$ . The space  $Y$  has the basis  $\{\phi_\ell \mid \ell = 1, \dots, L\}$  with the orthogonality property  $Q(\phi_\ell, \phi_{\ell'}) = 0$  for  $\ell \neq \ell'$ .

We observe that, by the orthogonality of  $Y_j$  with  $Y_i$  for  $i \neq j$  (see Lemma 3.4) and by the choice of a basis in each  $Y_j$ , the functions  $\phi_\ell$  are linearly independent. In particular, the dimension of the space  $Y$  is  $L \geq 0$ .

*The space  $B$ .* Let us consider another space, the space  $B$  of bounded solutions. That space was extensively used in [25] (where it was named  $X$ ). In order to impose a boundedness property, we introduce the norm  $\|U\|_{sL} := \sup_{r \in 2\pi\mathbb{Z}} \|U|_{W_r}\|_{L^2(W_r)}$  for functions  $U \in L^2_{\text{loc}}(\Omega)$ , where  $W_r = (r, r + 2\pi) \times S$ . The space of bounded homogeneous solutions is defined as

$$(4.2) \quad B := \{U \in H_{\text{loc}}(\text{curl}, \Omega) \mid U \text{ solves (1.4) for } f_e = f_h = 0, \|U\|_{sL} < \infty\}.$$

It is clear that every quasiperiodic homogeneous solutions is a bounded homogeneous solution:  $Y \subset B$ . Our aim is to show that the spaces  $Y$  and  $B$  actually coincide. When this is shown, we know that every bounded homogeneous solution of Maxwell's equations is a linear combination of Floquet-modes.

**Theorem 4.1** (Characterization of bounded homogeneous solutions). *When Assumption 3.1 holds, then the spaces  $Y$  of (4.1) and  $B$  of (4.2) coincide,*

$$(4.3) \quad Y = B.$$

*Proof. Step 1: Preparations.* The inclusion  $Y \subset B$  is clear, since every Floquet-mode is bounded. We know that  $Y$  has the dimension  $\dim Y = L$  since  $Y$  is spanned by  $(\phi_\ell)_{1 \leq \ell \leq L}$ . In order to show  $B = Y$ , it is therefore sufficient to show  $\dim B \leq L$ .

In this proof, we use a solution to the Maxwell radiation problem. For an arbitrary  $M > 0$  we choose the cut-off functions  $\rho_\pm$  so that the support of  $\rho'_\pm$  is contained in  $(-M, M)$ . For arbitrary  $R > M$ , we furthermore use the piecewise affine cut-off function  $\vartheta_R : \mathbb{R} \rightarrow [0, 1]$  with  $\vartheta_R(s) = 1$  for every  $s \in [-R, R]$ ,  $\vartheta_R(s) = 0$  for  $|s| \geq R + 2\pi$ , and linearly affine on  $[-R - 2\pi, -R]$  and on  $[R, R + 2\pi]$ . We interpret  $\vartheta_R$  also as a function on  $\Omega$  by setting  $\vartheta_R(x) := \vartheta_R(x_1)$ .

Let us recall statements of Theorem 3.9. The theorem provides, for  $f_e, f_h \in L_*^2(\Omega, \mathbb{C}^3)$  of (1.5), a solution  $u = u^{\text{prop}} + u^{\text{rad}}$ , where  $u^{\text{prop}}$  is given by coefficients  $(a_\ell)_\ell$  that are determined in (3.15). The coefficients  $(a_\ell)_\ell$  depend linearly and continuously on  $f_e$  and  $f_h$ . We will use these facts for  $f = f_h$  and  $f_e = 0$ .

We consider an arbitrary element  $U \in B$ . Our aim is to show that  $U$  can be written as a linear combination of the functions  $(\phi_\ell)_{1 \leq \ell \leq L}$ . When this is achieved, we know  $\dim B \leq L$  and the proof of the theorem is complete.

*Step 2: The scalar product of an element  $U \in B$  and a test-function  $f$ .* We choose a test-function  $f = f_h \in L_*^2(\Omega)$  with compact support. This proof is based on the evaluation of the  $L^2(\Omega)$ -scalar product  $\langle U, f \rangle$ .

We use Theorem 3.9 and consider the solution  $u = u^{\text{prop}} + u^{\text{rad}}$  of system (1.4), the radiation condition introduces coefficients  $(a_\ell)_{1 \leq \ell \leq L}$ . The right hand side of the system is  $f_h = f$  and  $f_e = 0$ . Using  $U\vartheta_R$  as a test-function in (1.4), we find

$$(4.4) \quad \int_{\Omega} \left\{ \frac{1}{\varepsilon} \operatorname{curl} u \cdot \operatorname{curl}(\bar{U}\vartheta_R) - \omega^2 \mu u \cdot \bar{U}\vartheta_R \right\} = -i\omega \int_{\Omega} f \cdot \bar{U}\vartheta_R = -i\omega \int_{\Omega} f \cdot \bar{U},$$

where the last equation holds for sufficiently large  $R$  since  $f$  has compact support.

We now re-write the left hand side of (4.4). We want to exploit that it coincides, up to a complex conjugation and terms involving derivatives of  $\vartheta_R$ , with the weak equation for  $U$  (which has the right hand side  $f_e = f_h = 0$ ) for the test-function  $u\vartheta_R$ . With a calculation as in the proof of Theorem 3.9, Step 1, we find that the left hand side of (4.4) coincides with

$$\begin{aligned} & \frac{1}{2\pi} \int_{W_R} \frac{1}{\varepsilon} [(\operatorname{curl} u \times \bar{U}) - (\operatorname{curl} \bar{U} \times u)] \cdot e_1 \\ & - \frac{1}{2\pi} \int_{W_{-R-2\pi}} \frac{1}{\varepsilon} [(\operatorname{curl} u \times \bar{U}) - (\operatorname{curl} \bar{U} \times u)] \cdot e_1, \end{aligned}$$

where  $W_r = (r, r + 2\pi) \times S$ .

We recall the decomposition  $u = u^{\text{prop}} + u^{\text{rad}}$ . In the limit  $R \rightarrow \infty$ , the contributions of  $u^{\text{rad}}$  in the above expression vanish by the decay of  $u^{\text{rad}}$ . The contributions of  $u^{\text{prop}}$  are independent of  $R$  for  $R > M$ . Inserting  $u^{\text{prop}} = \sum_{\ell=1}^L a_\ell \rho_\ell \phi_\ell$ , we conclude that the left hand side of (4.4) converges, for  $R \rightarrow \infty$ , to

$$\sum_{\ell=1}^L a_\ell \operatorname{sign} Q(\phi_\ell, \phi_\ell) \lim_{R \rightarrow \infty} \frac{1}{2\pi} \int_{W^\ell(R)} \frac{1}{\varepsilon} [(\operatorname{curl} \phi_\ell \times \bar{U}) - (\operatorname{curl} \bar{U} \times \phi_\ell)] \cdot e_1,$$

where  $W^\ell(R) = W_R$  for  $\ell$  with  $\lambda_\ell = Q(\phi_\ell, \phi_\ell) > 0$ , and  $W^\ell(R) = W_{-R-2\pi}$  for  $\ell$  with  $\lambda_\ell = Q(\phi_\ell, \phi_\ell) < 0$ . Our calculation provides, in particular, that the limit exists. Altogether, we obtain from (4.4) the relation

$$(4.5) \quad -i\omega \langle f, U \rangle_{L^2(\Omega)} = \sum_{\ell=1}^L c_\ell a_\ell,$$

where the complex numbers  $c_\ell$  depend on  $U$ , but not on  $f$ . Inserting  $a_\ell$  from (3.15) we obtain

$$(4.6) \quad \langle f, U \rangle_{L^2(\Omega)} = \sum_{\ell=1}^L c_\ell \frac{2\pi i}{|Q(\phi_\ell, \phi_\ell)|} \langle f, \phi_\ell \rangle_{L^2(\Omega)}.$$



Since  $f$  was chosen arbitrarily, this relation determines  $U$ . We find

$$(4.7) \quad U = \sum_{\ell=1}^L c_\ell \frac{2\pi i}{|Q(\phi_\ell, \phi_\ell)|} \phi_\ell.$$

This shows that the arbitrarily chosen element  $U \in B$  can be written as a linear combination of the functions  $(\phi_\ell)_{1 \leq \ell \leq L}$  and concludes the proof.  $\square$

## 5. A COMPACTLY PERTURBED MEDIUM

This section is devoted to more complex media, we recall that a medium is represented by the coefficients  $\varepsilon$  and  $\mu$ . We assume that outside a compact subset of  $\bar{\Omega}$ , the coefficients coincide with  $2\pi$ -periodic functions (as considered above). But, within a central region in  $\Omega$ , the coefficients can be arbitrary positive functions. We denote this situation as ‘‘a compactly perturbed medium’’. Let us turn to the concise mathematical description.

For some  $R > 0$ , we use the cylinder  $Z := \Omega_R = (-R, R) \times S$  and assume

$$(5.1) \quad \varepsilon_{\text{pert}} = \varepsilon - q_\varepsilon, \quad \mu_{\text{pert}} = \mu - q_\mu, \quad \text{supp}(q_\varepsilon), \text{supp}(q_\mu) \subset Z,$$

where  $\varepsilon$  and  $\mu$  have a positive upper and lower bound and are  $2\pi$ -periodic. We always demand that Assumption 3.1 holds for  $\varepsilon$  and  $\mu$ . Regarding the perturbed coefficients, we also assume that  $\varepsilon_{\text{pert}}$  and  $\mu_{\text{pert}}$  are of class  $L^\infty(\Omega)$  and have a positive lower bound. System (1.1) with the coefficients  $\varepsilon_{\text{pert}}$  and  $\mu_{\text{pert}}$  can be written as

$$(5.2) \quad \begin{aligned} \text{curl } H + i\omega \varepsilon E &= i\omega q_\varepsilon E + f_e, \\ -\text{curl } E + i\omega \mu H &= i\omega q_\mu H - f_h. \end{aligned}$$

We seek for solutions  $(E, H)$  such that  $H$  satisfies the radiation condition of Definition 3.7. We use the cut-off functions  $\rho_\ell$  of Definition 3.6 and assume that the support of  $\partial_{x_1} \rho$  is contained in  $Z$ . The propagating solutions to the homogeneous system with periodic coefficients are denoted as  $(E_\ell, H_\ell)$ . The radiation condition demands that there exist coefficients  $(a_\ell)_{1 \leq \ell \leq L} \in \mathbb{C}^L$  such that, decomposing the solution  $(E, H)$  as

$$(5.3) \quad (E, H) = (E^{\text{rad}}, H^{\text{rad}}) + \sum_{\ell=1}^L a_\ell \rho_\ell (E_\ell, H_\ell),$$

the first part satisfies  $(E^{\text{rad}}, H^{\text{rad}}) \in H_0(\text{curl}, \Omega) \times H(\text{curl}, \Omega)$ .

Our first aim is to write this system in a compact form. In this section, we use the notations  $X := H_0(\text{curl}, \Omega) \times H(\text{curl}, \Omega)$  and  $Y := L^2(\Omega, \mathbb{C}^3) \times L^2(\Omega, \mathbb{C}^3)$  and

$$u^{\text{rad}} := (E^{\text{rad}}, H^{\text{rad}}) \in X, \quad f := (f_e, -f_h) \in Y, \quad \phi_\ell := (E_\ell, H_\ell).$$

We introduce the operators  $D : X \rightarrow Y$  and  $\xi, Q : Y \rightarrow Y$ ,

$$D := \begin{pmatrix} 0 & \text{curl} \\ -\text{curl} & 0 \end{pmatrix}, \quad \xi := \begin{pmatrix} \varepsilon & 0 \\ 0 & \mu \end{pmatrix}, \quad Q := \begin{pmatrix} q_\varepsilon & 0 \\ 0 & q_\mu \end{pmatrix}.$$

With this notation, equation (5.2) takes the form

$$(5.4) \quad (D + i\omega \xi)u = i\omega Qu + f.$$

The propagating waves are solutions to the homogeneous system; in the new notation, this condition reads  $(D + i\omega \xi)\phi_\ell = 0$  for every  $\ell \leq L$ .

With the decomposition (5.3) of  $u$ , we can write the differential equation (5.4) in the unknown  $u^{\text{rad}}$ . Using the abbreviation  $\varphi_\ell := (D + i\omega \xi)(\rho_\ell \phi_\ell)$ , the equation takes the form

$$(5.5) \quad (D + i\omega \xi)u^{\text{rad}} + \sum_{\ell=1}^L a_\ell \varphi_\ell = i\omega Qu^{\text{rad}} + i\omega \sum_{\ell=1}^L a_\ell Q(\rho_\ell \phi_\ell) + f.$$

We note that the functions  $\varphi_\ell$ ,  $Qu^{\text{rad}}$ , and  $Q(\rho_\ell \phi_\ell)$  are all supported in  $Z = \Omega_R$ . On  $f$  we assume the fast decay  $f_e, f_h \in L_*^2(\Omega, \mathbb{C}^3)$ .

It is our first aim to show a Fredholm property: If (5.5) possesses no nontrivial solution  $(u^{\text{rad}}, a)$  for  $f = 0$ , then (5.5) possesses a solution  $(u^{\text{rad}}, a) \in X \times \mathbb{C}^L$  for every right hand side  $f \in L_*^2(\Omega, \mathbb{C}^3) \times L_*^2(\Omega, \mathbb{C}^3)$ . Since (5.5) is equivalent to (5.2), this shows also the Fredholm property for the original Maxwell system in a perturbed medium.

We recall from Theorem 3.9 that, in the unperturbed case  $Q = 0$ , system (5.5) has a unique solution pair  $(u^{\text{rad}}, a)$ .

**5.1. Helmholtz decompositions and reformulation.** We use several Helmholtz decompositions. In Appendix A, the decompositions  $H_0(\text{curl}, \Omega) = D^{(E)} \oplus G^{(E)}$  for the electric field, and  $H(\text{curl}, \Omega) = D^{(H)} \oplus G^{(H)}$  for the magnetic field are given; they differ in the weight ( $\varepsilon$  and  $\mu$ , respectively) and in the boundary condition for the potential. When we apply these decompositions to the product space  $X = H_0(\text{curl}, \Omega) \times H(\text{curl}, \Omega)$ , we find the decomposition

$$(5.6) \quad X = X_D \oplus X_G := (D^{(E)} \times D^{(H)}) \oplus (G^{(E)} \times G^{(H)}).$$

Accordingly, an element  $u^{\text{rad}} \in X$  is written as  $u^{\text{rad}} = u_D^{\text{rad}} + u_G^{\text{rad}}$ . An element  $u_G^{\text{rad}} \in X_G$  is of the form  $u_G^{\text{rad}} = (\nabla \psi_E, \nabla \psi_H)$  with  $\psi_E \in H_0^1(\Omega)$  and  $\psi_H \in \dot{H}^1(\Omega)$  where we refer to Appendix A for the definition of the space  $\dot{H}^1(\Omega)$ .

Unfortunately, regarding right hand sides, we need another decomposition:

$$(5.7) \quad f = (f_e, -f_h) \in Y := L^2(\Omega)^2 = Y_D \oplus Y_G,$$

and we write an element  $f \in Y$  as  $f = f^D + f^G$ . On  $Y$ , we use the scalar product defined by  $\langle f, g \rangle = \langle (f_e, -f_h), (g_e, -g_h) \rangle = \int_\Omega \varepsilon^{-1} f_e \bar{g}_e + \mu^{-1} f_h \bar{g}_h$ . The subspace  $Y_G$  consists of gradients, more precisely, an element  $f^G \in Y_G$  has the form  $f^G = (\varepsilon \nabla \psi_E, \mu \nabla \psi_H)$  with  $\psi_E \in H_0^1(\Omega)$  and  $\psi_H \in \dot{H}^1(\Omega)$ . The subspace  $Y_D$  is the orthogonal complement of  $Y_G$  in  $Y$ . In particular,  $f^D \in Y_D$  has the property that its components satisfy  $\int_\Omega f_e^D \cdot \nabla \psi_E = 0$  and  $\int_\Omega f_h^D \cdot \nabla \psi_H = 0$  for all  $\psi_E \in H_0^1(\Omega)$  and  $\psi_H \in \dot{H}^1(\Omega)$ .

In equation (5.5), we write  $u^{\text{rad}} = u_D^{\text{rad}} + u_G^{\text{rad}}$  for the unknown. Furthermore, we project the equation to the two subspaces  $Y_D$  (with projection  $\pi_D^Y$ ) and  $Y_G$  (with projection  $\pi_G^Y$ ). We find the following system, equivalent to (5.5):

$$(5.8) \quad \begin{aligned} & \pi_D^Y(D + i\omega \xi)u_D^{\text{rad}} + \pi_D^Y(D + i\omega \xi)u_G^{\text{rad}} + \sum_{\ell=1}^L a_\ell \pi_D^Y \varphi_\ell \\ & = i\omega \pi_D^Y Q(u_D^{\text{rad}} + u_G^{\text{rad}}) + i\omega \sum_{\ell=1}^L a_\ell \pi_D^Y Q(\rho_\ell \phi_\ell) + \pi_D^Y f, \end{aligned}$$

$$\begin{aligned}
(5.9) \quad & \pi_G^Y(D + i\omega \xi)u_D^{\text{rad}} + \pi_G^Y(D + i\omega \xi)u_G^{\text{rad}} + \sum_{\ell=1}^L a_\ell \pi_G^Y \varphi_\ell \\
& = i\omega \pi_G^Y Q(u_D^{\text{rad}} + u_G^{\text{rad}}) + i\omega \sum_{\ell=1}^L a_\ell \pi_G^Y Q(\rho_\ell \phi_\ell) + \pi_G^Y f.
\end{aligned}$$

These equations simplify considerably when we use the following facts: (i)  $Du_G^{\text{rad}} = 0$ , since the curl of a gradient vanishes. (ii)  $\pi_D^Y(\xi u_G^{\text{rad}}) = 0$  and  $\pi_G^Y(\xi u_G^{\text{rad}}) = \xi u_G^{\text{rad}}$ , because of  $\xi u_G^{\text{rad}} \in Y_G$ . (iii)  $\pi_D^Y(\xi u_D^{\text{rad}}) = \xi u_D^{\text{rad}}$  and  $\pi_G^Y(\xi u_D^{\text{rad}}) = 0$  because of  $\xi u_D^{\text{rad}} \in Y_D$ . (iv)  $\pi_D^Y Du_D^{\text{rad}} = Du_D^{\text{rad}}$  and  $\pi_G^Y Du_D^{\text{rad}} = 0$  since every curl is  $L^2$ -orthogonal to gradients. In this last point, one has to be careful: The first entry is of the form  $\langle \text{curl } H^{\text{rad}}, \varepsilon \nabla \psi_E \rangle_{1/\varepsilon} = \langle \text{curl } H^{\text{rad}}, \nabla \psi_E \rangle_{L^2} = 0$  because of  $\psi_E \in H_0^1(\Omega)$ . The second entry is of the form  $\langle -\text{curl } E^{\text{rad}}, \mu \nabla \psi_H \rangle_{1/\mu} = \langle -\text{curl } E^{\text{rad}}, \nabla \psi_H \rangle_{L^2} = 0$  because of the boundary condition  $E^{\text{rad}} \times \nu = 0$ , encoded in  $E^{\text{rad}} \in H_0(\text{curl}, \Omega)$ .

Omitting the corresponding terms, system (5.8)–(5.9) takes the equivalent form

$$\begin{aligned}
(5.10) \quad & (D + i\omega \xi)u_D^{\text{rad}} + \sum_{\ell=1}^L a_\ell \pi_D^Y \varphi_\ell \\
& = i\omega \pi_D^Y Q u_D^{\text{rad}} + i\omega \pi_D^Y Q u_G^{\text{rad}} + i\omega \sum_{\ell=1}^L a_\ell \pi_D^Y Q(\rho_\ell \phi_\ell) + \pi_D^Y f,
\end{aligned}$$

$$\begin{aligned}
(5.11) \quad & i\omega \pi_G^Y(\xi u_G^{\text{rad}}) + \sum_{\ell=1}^L a_\ell \pi_G^Y \varphi_\ell \\
& = i\omega \pi_G^Y Q u_G^{\text{rad}} + i\omega \pi_G^Y Q u_D^{\text{rad}} + i\omega \sum_{\ell=1}^L a_\ell \pi_G^Y Q(\rho_\ell \phi_\ell) + \pi_G^Y f.
\end{aligned}$$

We will see that (5.10) is a Maxwell system, while (5.11) is a Poisson problem.

**5.2. Solution of (5.11).** Our aim is to solve the second equation for  $u_G^{\text{rad}}$ , assuming that  $u_D^{\text{rad}}$  and  $(a_\ell)_\ell$  are given. We have to study the problem

$$(5.12) \quad i\omega \pi_G^Y((\xi - Q)u_G^{\text{rad}}) = g \in Y_G \subset L^2(\Omega, \mathbb{C}^3)^2.$$

Solving (5.12) means that we want to achieve that the  $Y_G$ -part of the function  $i\omega(\xi - Q)u_G^{\text{rad}} - g$  vanishes. This is the case if, and only if,  $i\omega(\xi - Q)u_G^{\text{rad}} - g$  is  $Y$ -orthogonal to the subspace  $Y_G$ . Equation (5.12) is therefore identical to

$$(5.13) \quad \int_{\Omega} (i\omega(\xi - Q)u_G^{\text{rad}}) \cdot (\nabla \varphi_E, \nabla \varphi_H) = \int_{\Omega} g \cdot (\nabla \varphi_E, \nabla \varphi_H)$$

for all  $(\varphi_E, \varphi_H) \in H_0^1(\Omega) \times \dot{H}^1(\Omega)$ . Recalling  $u_G^{\text{rad}} = (\nabla \psi_E, \nabla \psi_H)$  shows that this is a Poisson problem for  $(\psi_E, \psi_H)$ , which is uniquely solvable because of strict positivity of  $\xi - Q$ , see Lemma C.1. Note that we impose a Dirichlet boundary condition for  $\psi_E$ , while we impose no boundary condition for  $\psi_H$  (leading to a Neumann boundary condition).

The construction provides a solution operator for equation (5.12),

$$(5.14) \quad \mathcal{G} : Y_G \ni g \mapsto u_G^{\text{rad}} = (\nabla \psi_E, \nabla \psi_H) \in X_G.$$

This operator is linear and bounded.

5.3. **Solution of (5.10).** We know that the solution of (5.11) is given by

$$u_G^{\text{rad}} = \mathcal{G} \left( i\omega \pi_G^Y Q u_D^{\text{rad}} + i\omega \sum_{\ell=1}^L a_\ell \pi_G^Y Q(\rho_\ell \phi_\ell) + \pi_G^Y f - \sum_{\ell=1}^L a_\ell \pi_G^Y \varphi_\ell \right),$$

and can insert this expression into (5.10). Writing now  $\tilde{u}_D$  for the unknown, the remaining equation reads

$$(5.15) \quad (D + i\omega \xi) \tilde{u}_D + \sum_{\ell=1}^L a_\ell \pi_D^Y \varphi_\ell = i\omega \pi_D^Y Q \tilde{u}_D + i\omega \sum_{\ell=1}^L a_\ell \pi_D^Y Q(\rho_\ell \phi_\ell) + \pi_D^Y f \\ + i\omega \pi_D^Y Q \mathcal{G} \left( i\omega \pi_G^Y Q \tilde{u}_D + i\omega \sum_{\ell=1}^L a_\ell \pi_G^Y Q(\rho_\ell \phi_\ell) + \pi_G^Y f - \sum_{\ell=1}^L a_\ell \pi_G^Y \varphi_\ell \right).$$

Our next aim is to construct a map that is closely related to this equation. We want to map a pair  $(u_D^{\text{old}}, a^{\text{old}}) \in L^2(Z, \mathbb{C}^3)^2 \times \mathbb{C}^L$  to a new pair  $(u_D^{\text{new}}, a^{\text{new}}) \in L^2(Z, \mathbb{C}^3)^2 \times \mathbb{C}^L$ . Let us give the construction of the map. In a first step we seek for  $(\tilde{u}_D^{\text{new}}, a^{\text{new}}) \in X_D \times \mathbb{C}^L$  that solves

$$(5.16) \quad (D + i\omega \xi) \tilde{u}_D^{\text{new}} + \sum_{\ell=1}^L a_\ell^{\text{new}} \pi_D^Y \varphi_\ell = \tilde{f}$$

in  $\Omega$ , where the right hand side is defined as

$$(5.17) \quad \tilde{f} := i\omega \pi_D^Y Q u_D^{\text{old}} - \omega^2 \pi_D^Y Q \mathcal{G} \pi_G^Y Q u_D^{\text{old}} + i\omega \sum_{\ell=1}^L a_\ell^{\text{old}} \pi_D^Y Q(\rho_\ell \phi_\ell) \\ + i\omega \pi_D^Y Q \mathcal{G} \left( i\omega \sum_{\ell=1}^L a_\ell^{\text{old}} \pi_G^Y Q(\rho_\ell \phi_\ell) - \sum_{\ell=1}^L a_\ell^{\text{old}} \pi_G^Y \varphi_\ell \right).$$

We claim that the existence and uniqueness result of Theorem 3.9 allows to solve equation (5.16). Theorem 3.9 provides a solution  $\tilde{u} = \tilde{u}^{\text{rad}} + \tilde{u}^{\text{prop}}$  of  $(D + i\omega \xi) \tilde{u} = \tilde{f}$  (we show below that  $\tilde{f} \in L_*^2(\Omega, \mathbb{C}^3)^2$  is satisfied). Then  $(D + i\omega \xi) \tilde{u}^{\text{prop}} = \sum_{\ell=1}^L a_\ell^{\text{new}} \varphi_\ell$  for some coefficients  $a_\ell^{\text{new}}$ . Decomposing  $\tilde{u}^{\text{rad}} = \tilde{u}_D + \tilde{u}_G$ , the pair  $(\tilde{u}_D, a_\ell^{\text{new}})$  solves (5.16). Indeed,  $(D + i\omega \xi) \tilde{u}_G \in Y_G$ , since the curl of a gradient vanishes and  $\xi$  maps from  $X_G$  to  $Y_G$ . Therefore,  $(D + i\omega \xi) \tilde{u}_D = \pi_D^Y (D + i\omega \xi) \tilde{u}_D = \pi_D^Y (D + i\omega \xi) \tilde{u}^{\text{rad}} = \pi_D^Y \tilde{f} - \pi_D^Y (D + i\omega \xi) \tilde{u}^{\text{prop}} = \tilde{f} - \pi_D^Y (D + i\omega \xi) \tilde{u}^{\text{prop}}$ , which shows that  $(\tilde{u}_D, a_\ell^{\text{new}})$  solves (5.16).

The comparison of (5.16) with (5.15) shows that we added the superscripts “new” on the left hand side and the superscripts “old” on the right hand side. Furthermore, we have omitted the terms containing  $f$  in the definition of  $\tilde{f}$ . The function  $u_D^{\text{new}} \in L^2(Z, \mathbb{C}^3)$  is defined as the restriction of  $\tilde{u}_D^{\text{new}}$  to  $Z$ ,

$$u_D^{\text{new}} := \tilde{u}_D^{\text{new}}|_Z.$$

This concludes the construction of the iteration operator

$$(5.18) \quad \mathcal{T} : L^2(Z, \mathbb{C}^3)^2 \times \mathbb{C}^L \ni (u_D^{\text{old}}, a^{\text{old}}) \mapsto (u_D^{\text{new}}, a^{\text{new}}) \in L^2(Z, \mathbb{C}^3)^2 \times \mathbb{C}^L.$$

We note that the definition of  $\tilde{f}$  in (5.17) uses the input variable  $u_D^{\text{old}}$  only with a factor  $Q$ . This shows that the restriction of the unknown to the domain  $Z$  is not related to a loss of relevant information for the iteration.

**Lemma 5.1** (The iteration operator). *We assume, as before, that  $\varepsilon$  and  $\mu$  are real, of class  $L^\infty(W)$ , with a positive lower bound. Then the operator  $\mathcal{T}$  of (5.18) is well-defined and compact.*

*Proof.* The fact that  $\mathcal{T}$  is well-defined relies on a property of  $\pi_D^Y$ . In the definition of  $\tilde{f}$  we have to evaluate the projection  $\pi_D^Y$  for an argument that is a compactly supported function. When we identify a function that is supported on  $Z$  with its trivial extension, we can regard  $L^2(Z, \mathbb{C}^3)^2$  as a subspace of  $L^2(\Omega, \mathbb{C}^3)^2$ . With this convention, we claim that

$$(5.19) \quad \pi_D^Y : L^2(Z, \mathbb{C}^3)^2 \rightarrow L_*^2(\Omega, \mathbb{C}^3)^2$$

is a bounded linear operator. Once this is shown, by definition of  $\tilde{f}$  in (5.17), it is clear that  $\mathcal{T}$  is well-defined.

In order to show (5.19), we have to recall the construction of  $\pi_D^Y$ . The projection acts on a function  $f = (f_e, f_h)$ , and the two components are treated independent of each other. Regarding the first component, we want to find, for  $f_e \in L^2(Z, \mathbb{C}^3)$  with support in  $Z$ , the projection onto  $D^{(E)}$ . This projection is given by  $f_e - \varepsilon \nabla \psi$ , where  $\psi \in H_0^1(\Omega, \mathbb{C})$  solves the problem

$$\int_{\Omega} \varepsilon \nabla \psi \cdot \nabla \bar{\phi} = \int_{\Omega} f_e \cdot \nabla \bar{\phi} \quad \text{for all } \phi \in H_0^1(\Omega).$$

Solutions  $\psi$  of this equation have exponential decay of  $\nabla \psi$  for  $|x_1| \rightarrow \infty$ , which is shown in Lemma C.1 of Appendix C. In that lemma, also the Neumann problem is treated and, hence, an analogous result holds for the projection of  $f_h$ . These two facts provide (5.19).

*Compactness.* In order to show the compactness of  $\mathcal{T}$ , we have to recall the last step in the construction of  $\mathcal{T}$ : A function  $u_D^{\text{old}} \in L^2(Z, \mathbb{C}^3)$  is, in the main part of the construction, mapped to a function  $\tilde{u}_D^{\text{new}} \in H_{\text{loc}}(\text{curl}, \Omega)$ , which is the solution of a radiation problem. When we restrict  $\tilde{u}_D^{\text{new}}$  to any bounded subdomain  $\Omega_R = (-R, R) \times S$ , then the map  $L^2(Z, \mathbb{C}^3) \ni u_D^{\text{old}} \mapsto \tilde{u}_D^{\text{new}}|_{\Omega_R} \in H(\text{curl}, \Omega_R)$  is bounded.

We choose  $R$  large such that  $\bar{Z}$  is contained in  $\Omega_R$ , and a cut-off function  $\eta \in C^2(\Omega)$  depending only on  $x_1$  such that  $\eta(x) = 1$  for  $x \in Z$  and  $\eta(x) = 0$  for  $x \in \Omega \setminus \Omega_R$ . With this construction, the map

$$\mathcal{T}' : L^2(Z, \mathbb{C}^3) \ni u_D^{\text{old}} \mapsto \tilde{u}_D^{\text{new}} \eta \in L^2(\Omega_R, \mathbb{C}^3)$$

is bounded. Furthermore, for bounded arguments  $u_D^{\text{old}}$ , both, the curl of the right hand side  $\tilde{u}_D^{\text{new}} \eta$  and the divergence of  $\xi \tilde{u}_D^{\text{new}} \eta$  are bounded in  $L^2(\Omega_R)$ . This follows from the facts that the divergence of  $\xi \tilde{u}_D^{\text{new}}$  vanishes and that the curl of  $\tilde{u}_D^{\text{new}}$  (that is,  $D\tilde{u}_D^{\text{new}}$ ) is bounded in  $L^2$ . The first component of  $\tilde{u}_D^{\text{new}} \eta$  satisfies a (tangential) Dirichlet conditions on all boundaries of  $\Omega_R$ , the second component satisfies a Neumann condition. Lemma A.2 can be used to obtain compactness of the second (the magnetic) component of  $u$ , Lemma A.2 with the spaces of (c) yields compactness of the first (the electric) component. We note that the lemma remains valid when  $W = (0, 2\pi) \times S$  is replaced by  $\Omega_R$ . This yields the compactness of  $\mathcal{T}'$ , and hence also the compactness of  $\mathcal{T}$ , which is given by the further restriction of the function to  $Z$ .  $\square$

In order to include the given right hand side  $f$  of (5.7) into the equation, we finally define  $(\tilde{u}_D^\circ, a^\circ) \in X \times \mathbb{C}^L$  as the unique solution of

$$(5.20) \quad (D + i\omega\xi)\tilde{u}_D^\circ + \sum_{\ell=1}^L a_\ell^\circ \pi_D^Y \varphi_\ell = \pi_D^Y f + i\omega \pi_D^Y Q \mathcal{G} \pi_G^Y f$$

on  $\Omega$ . We refer to the discussion after (5.16) for the fact that the existence and uniqueness Theorem 3.9 provides a solution to this equation. We set  $u_D^\circ := \tilde{u}_D^\circ|_Z$ .

Let us not forget that we are interested in the Maxwell equations in a locally perturbed periodic medium, i.e., in (5.2). The first part of this section was devoted to an equivalent re-formulation of this system. The result was that (5.2) is equivalent to equation (5.15). We now claim that (5.15) is equivalent to the following problem for  $(u_D, a) \in L^2(Z, \mathbb{C}^3)^2 \times \mathbb{C}^L$ :

$$(5.21) \quad (u_D, a) = (u_D^\circ, a^\circ) + \mathcal{T}(u_D, a).$$

Let us verify this claim. To this end, we first consider a solution  $(u_D, a)$  to (5.21). We use  $(\tilde{u}_D^\circ, a^\circ)$  as constructed in (5.20) and the function  $(\tilde{u}_D^{\text{new}}, a^{\text{new}})$  from the definition of  $\mathcal{T}(u_D, a)$  for  $(u_D^{\text{old}}, a^{\text{old}}) := (u_D, a)$ . We claim that  $(\tilde{u}_D, a) := (\tilde{u}_D^\circ + \tilde{u}_D^{\text{new}}, a^\circ + a^{\text{new}})$  is a solution of (5.15).

In the subsequent calculation, we use the definition of  $(\tilde{u}_D, a)$  in the first equation, the definition of  $(\tilde{u}_D^\circ, a^\circ)$  and (5.16) in the second equation, and the definition of  $\tilde{f}$  in the last equation. We obtain

$$\begin{aligned} (D + i\omega\xi)\tilde{u}_D + \sum_{\ell=1}^L a_\ell \pi_D^Y \varphi_\ell &= (D + i\omega\xi)(\tilde{u}_D^{\text{new}} + \tilde{u}_D^\circ) + \sum_{\ell=1}^L (a_\ell^{\text{new}} + a_\ell^\circ) \pi_D^Y \varphi_\ell \\ &= \tilde{f} + \pi_D^Y f + i\omega \pi_D^Y Q \mathcal{G} \pi_G^Y f \\ &= i\omega \pi_D^Y Q u_D^{\text{old}} + \omega^2 \pi_D^Y Q \mathcal{G} \pi_G^Y Q u_D^{\text{old}} + i\omega \sum_{\ell=1}^L a_\ell^{\text{old}} \pi_D^Y Q (\rho_\ell \phi_\ell) \\ &\quad - i\omega \pi_D^Y Q \sum_{\ell=1}^L a_\ell^{\text{old}} \mathcal{G} \left( i\omega \pi_G^Y Q (\rho_\ell \phi_\ell) - \pi_G^Y \varphi_\ell \right) + \pi_D^Y f + i\omega \pi_D^Y Q \mathcal{G} \pi_G^Y f. \end{aligned}$$

From (5.21) we find  $u_D^{\text{old}} = \tilde{u}_D^{\text{new}}|_Z + \tilde{u}_D^\circ|_Z = \tilde{u}_D|_Z$  and  $a_\ell^{\text{old}} = a_\ell^{\text{new}} + b_\ell^\circ = a_\ell$ . This shows that  $(\tilde{u}_D, a)$  is a solution of (5.15).

Vice versa, let  $(\tilde{u}_D, a)$  be a solution of (5.15). By the definition of  $\mathcal{T}$ , it is clear that  $(u_D, a)$  with  $u_D := \tilde{u}_D|_Z$  is a solution of (5.21).

We have shown that the system with a locally perturbed medium is equivalent to (5.21), which is of Fredholm type: The operator that acts on the unknown  $(u_D, a)$  is of the form  $\text{id} - \mathcal{T}$  (identity plus compact) by Lemma 5.1. We therefore obtain Fredholm's alternative for equation (5.5), and thus for (5.2). In particular, there holds: If the homogeneous system admits only the trivial solution  $(u^{\text{rad}}, a) = (0, 0)$ , then system (5.2) has a unique solution  $(u^{\text{rad}}, a) \in X \times \mathbb{C}^L$  for every right hand side.

In the proof of the subsequent theorem, we show that any solution  $(u^{\text{rad}}, a) \in X \times \mathbb{C}^L$  of the homogeneous system (5.2) is necessarily radiating, i.e.  $a = 0$ . This property implies that Fredholm's alternative can be formulated in a strengthened way: If the homogeneous system admits only the trivial solution in  $L^2$ -spaces, then system (5.2) has a unique solution  $(u^{\text{rad}}, a) \in X \times \mathbb{C}^L$  for every right hand side.

**Theorem 5.2** (Fredholm alternative for perturbed media). *Let  $S \subset \mathbb{R}^2$  be a bounded Lipschitz domain and let  $\omega > 0$ . Let the coefficients  $\mu, \varepsilon \in L^\infty(\Omega)$  have positive lower bounds and let them be given as compact perturbations of periodic functions*

with positive lower bounds. We demand that Assumption 3.1 is satisfied for the periodic medium. Furthermore, let the homogeneous perturbed system, i.e. (5.2) for  $f_e = f_h = 0$ , admit only the trivial solution in  $H_0(\text{curl}, \Omega) \times H(\text{curl}, \Omega)$ . (In other words: Let  $\omega^2$  be not in the point spectrum of  $\mu_{\text{pert}}^{-1} \text{curl}(\varepsilon_{\text{pert}}^{-1} \text{curl})$ .) Then there exists a unique radiating solution to (5.2) for every  $(f_e, f_h)$  as in Theorem 3.9.

*Proof.* We consider a solution  $(u^{\text{rad}}, a) \in X \times \mathbb{C}^L$  of the homogeneous system (5.2) and want to prove  $a = 0$ . In this proof, we will work again with the magnetic field only. To avoid confusion with the pair  $u = (E, H)$ , we set  $v^{\text{rad}} = H^{\text{rad}}$  and  $v^{\text{prop}} = \sum_{\ell=1}^L a_\ell \rho_\ell \phi_\ell$ . It is our aim to show that  $v^{\text{prop}}$  vanishes.

The form  $Q$  was defined in (3.4), we modify this definition and set

$$\tilde{Q}_r(u, w) := i \int_{W_r} \frac{1}{\varepsilon_{\text{pert}}} [(\text{curl } u \times \bar{w}) - (\text{curl } \bar{w} \times u)] \cdot e_1,$$

where  $W_r = (r, r + 2\pi) \times S$ . Note that we made the position  $r$  variable and that we replaced the periodic coefficient  $\varepsilon$  by the perturbed coefficient  $\varepsilon_{\text{pert}}$ . As in (3.3) for the periodic case, one shows that  $\tilde{Q}_r(u, w)$  is independent of  $r \in \mathbb{R}$  for solutions  $u$  and  $w$  of  $\text{curl}(\varepsilon_{\text{pert}}^{-1} \text{curl } u) - \omega^2 \mu_{\text{pert}} u = 0$ .

We insert  $v = v^{\text{rad}} + v^{\text{prop}}$  in  $\tilde{Q}_r(v, v)$ . Because of  $v^{\text{rad}} \in H(\text{curl}, \Omega)$  and the uniform (with respect to  $r$ ) boundedness of  $\|v^{\text{prop}}\|_{H(\text{curl}, W_r)}$  we conclude that

$$\begin{aligned} \tilde{Q}_r(v, v) - \tilde{Q}_r(v^{\text{prop}}, v^{\text{prop}}) &= i \int_{W_r} \frac{1}{\varepsilon_{\text{pert}}} [(\text{curl } v^{\text{rad}} \times \overline{v^{\text{rad}}}) - (\text{curl } \overline{v^{\text{rad}}} \times v^{\text{rad}}) \\ &\quad + (\text{curl } v^{\text{rad}} \times \overline{v^{\text{prop}}}) - (\text{curl } \overline{v^{\text{prop}}} \times v^{\text{rad}}) \\ &\quad + (\text{curl } v^{\text{prop}} \times \overline{v^{\text{rad}}}) - (\text{curl } \overline{v^{\text{rad}}} \times v^{\text{prop}})] \cdot e_1 \end{aligned}$$

tends to zero as  $|r| \rightarrow \infty$ . We consider  $r \geq R$  such that  $\varepsilon_{\text{pert}}$  coincides with  $\varepsilon$  in  $W_r$ . From

$$\tilde{Q}_r(\phi_{\ell,j}, \phi_{\ell',j'}) = e^{i2\pi r(\alpha_j - \alpha_{j'})} Q(\phi_{\ell,j}, \phi_{\ell',j'}) = \delta_{j,j'} \delta_{\ell,\ell'} Q(\phi_{\ell,j}, \phi_{\ell,j})$$

follows

$$\tilde{Q}_r(v^{\text{prop}}, v^{\text{prop}}) = \sum_{j=1}^J \sum_{\ell: \lambda_{\ell,j} > 0} |a_{\ell,j}|^2 Q(\phi_{\ell,j}, \phi_{\ell,j}) \geq 0.$$

In the same way, for  $r \leq -R - 2\pi$ , we have  $\tilde{Q}_r(v^{\text{prop}}, v^{\text{prop}}) \leq 0$ . Since  $\tilde{Q}_r(v, v)$  is constant with respect to  $r$ , we conclude that  $\tilde{Q}_r(v, v)$  has to vanish. This also implies  $a_{\ell,j} = 0$  for all  $\ell, j$  and hence  $v^{\text{prop}} = 0$ .  $\square$

## 6. CONCLUDING REMARKS

**6.1. Limiting absorption principle.** In a limiting absorption principle, one studies the original problem, in our case (1.1) with real coefficients  $\varepsilon$  and  $\mu$ , and adds a term that introduces physical absorption of energy. In our setting, a natural choice is to replace  $\varepsilon$  by the complex (still  $x$ -dependent and  $2\pi$ -periodic) parameter  $\varepsilon + i\eta\sigma/\omega$ , where  $\eta > 0$  is a small real number and  $\sigma \in L^\infty(\Omega)$  is a positive  $2\pi$ -periodic function describing the conductivity of the medium. With this choice,  $\eta$  is a parameter for (small) ohmic losses in the system.

The new system is solvable with the Lax-Milgram lemma, the new sesquilinear form is coercive for positive  $\eta$ . Denoting the corresponding solutions by  $E^\eta$  and  $H^\eta$ , the relevant questions are: (i) Are the fields  $E^\eta$  and  $H^\eta$  in every compact subset of  $\bar{\Omega}$  bounded in  $L^2$ ? (ii) Are all weak limits  $E$  and  $H$  solutions to the original problem

(1.1) and do they satisfy the radiation condition? We say that a limiting absorption principle holds, when both questions can be answered in an affirmative sense.

For the Helmholtz equation in the waveguide geometry, a limiting absorption principle has been derived in several works, we mention once more [10], [13], and [17]. In view of the results and, moreover, the method of proof in [17], it is not difficult to show that the limiting absorption principle holds also in the above sense for the Maxwell system (1.1). It is interesting to note that in this case the inner product  $\langle \cdot, \cdot \rangle_{Y_j}$  used in the construction of the orthogonal basis  $\{\phi_{\ell,j} \mid \ell = 1, \dots, m_j\}$  in  $Y_j$  is given by

$$\langle u, v \rangle_{Y_j} = \frac{1}{\omega} \int_W \frac{\sigma}{\varepsilon^2} \operatorname{curl} u \cdot \operatorname{curl} \bar{v}.$$

In particular, this inner product – and thus the radiation condition – depends on the conductivity  $\sigma$ .

**6.2. Scattering problem.** Based on the results of Section 5, one can also study a scattering problem. Given a mode  $(E^{\text{inc}}, H^{\text{inc}}) = (E_{\ell,j}, H_{\ell,j})$ , which is interpreted as an incoming field, one is interested in a corresponding solution in the perturbed medium, which is given by  $\varepsilon_{\text{pert}}$  and  $\mu_{\text{pert}}$ . The problem is to determine the total field  $(E^{\text{tot}}, H^{\text{tot}}) = (E^{\text{inc}}, H^{\text{inc}}) + (E^s, H^s)$  which satisfies (5.2) for  $(f_e, f_h) = (0, 0)$  such that the scattered field  $(E^s, H^s)$  satisfies the radiation condition. We observe that  $(E^s, H^s)$  solves (5.2) for the (compactly supported) right hand side

$$(f_e, f_h) := (i\omega q_\varepsilon E^{\text{inc}}, -i\omega q_\mu H^{\text{inc}}).$$

Theorem 5.2 can be applied and provides the solution  $(E^s, H^s)$ .

We furthermore observe that also the situation of Section 4 can be considered for the perturbed system (5.2). By almost the same arguments as in the proof of Theorem 4.1, one can show that the space

$$\begin{aligned} \{ (E, H) \in H_{0,\text{loc}}(\operatorname{curl}, \Omega) \times H_{\text{loc}}(\operatorname{curl}, \Omega) \mid (E, H) \text{ solves (5.2) for} \\ (f_e, f_h) = (0, 0), \|E\|_{sL} + \|H\|_{sL} < \infty \} \end{aligned}$$

of bounded solutions coincides with the space spanned by the total fields  $(E_{\ell,j}^{\text{tot}}, H_{\ell,j}^{\text{tot}})$  of the above remark.

## APPENDIX A. HELMHOLTZ DECOMPOSITIONS AND COMPACTNESS

**A.1. The unbounded domain  $\Omega$ .** In this part we investigate Helmholtz decompositions in  $H(\operatorname{curl}, \Omega)$  and  $H_0(\operatorname{curl}, \Omega)$ . The letter “D” is used for the space with a condition on the divergence, the letter “G” is used for the space that is related to gradients. For the field  $E$ , we introduce

$$\begin{aligned} D^{(E)} &:= \left\{ E \in H_0(\operatorname{curl}, \Omega) \mid \int_\Omega \varepsilon E \cdot \nabla \psi = 0 \text{ for all } \psi \in H_0^1(\Omega) \right\}, \\ G^{(E)} &:= \left\{ E \in H_0(\operatorname{curl}, \Omega) \mid \exists \psi \in H_0^1(\Omega) : E = \nabla \psi \right\}. \end{aligned}$$

The definitions are such that the spaces are orthogonal in the space  $L^2(\Omega, \mathbb{C}^3)$  with the weighted scalar product  $\langle u, v \rangle = \int_\Omega \varepsilon u \cdot \bar{v}$ . Furthermore, since the (distributional) curl of a gradient always vanishes,  $\operatorname{curl}(\nabla \psi) = 0$ , the two subspaces are also orthogonal in  $H(\operatorname{curl}, \Omega)$  with the scalar product  $\langle u, v \rangle = \int_\Omega \varepsilon u \cdot \bar{v} + \operatorname{curl} u \cdot \operatorname{curl} \bar{v}$ . By construction,  $D^{(E)}$  is the  $H(\operatorname{curl}, \Omega)$ -orthogonal complement of  $G^{(E)}$ , we therefore have an orthogonal decomposition  $H_0(\operatorname{curl}, \Omega) = D^{(E)} \oplus G^{(E)}$ .



Related to (1.3), the decomposition implies the following: Let  $f_e \in L^2(\Omega)$  satisfy  $\int_{\Omega} f_e \cdot \nabla \psi = 0$  for all  $\psi \in H_0^1(\Omega, \mathbb{C})$ . In this case, since the left hand side of (1.3) vanishes for  $\phi = \nabla \psi \in G^{(E)}$ , we find  $E \in D^{(E)}$ .

An analogous construction can be made for the magnetic field. We must be very careful in the definition of  $G^{(H)}$ ; the space of gradients of  $H^1(\Omega)$ -potentials is not closed in  $H(\text{curl}, \Omega)$ . Loosely speaking, every limit of gradients is again (locally) a gradient, but its potential may fail to be in the space  $L^2(\Omega)$ . We therefore work with the Hilbert space where integrability is demanded only for the derivatives,  $\dot{H}^1(\Omega) := \{v \in L_{\text{loc}}^2(\Omega, \mathbb{C}) \mid \nabla v \in L^2(\Omega)\}$ , equipped with the inner product  $\langle u, v \rangle := \langle u, v \rangle_{L^2(W)} + \langle \nabla u, \nabla v \rangle_{L^2(\Omega)}$ . We use the closed subspaces

$$\begin{aligned} D^{(H)} &:= \left\{ H \in H(\text{curl}, \Omega) \mid \int_{\Omega} \mu H \cdot \nabla \psi = 0 \text{ for all } \psi \in \dot{H}^1(\Omega) \right\}, \\ G^{(H)} &:= \left\{ H \in H(\text{curl}, \Omega) \mid \exists \psi \in \dot{H}^1(\Omega) : H = \nabla \psi \right\}. \end{aligned}$$

In the above definition, it is important to use  $\dot{H}^1(\Omega)$  in order to achieve that  $G^{(H)}$  is a closed subspace. Let us verify that, indeed,  $G^{(H)}$  is closed. With this aim, we consider a sequence  $(\psi_j)_j$  with  $\psi_j \in \dot{H}^1(\Omega)$  such that  $(\nabla \psi_j)_j$  is convergent in  $H(\text{curl}, \Omega)$ . Upon subtracting a constant  $c_j \in \mathbb{C}$  and using the sequence  $\psi_j - c_j$ , we can assume the normalization  $\int_W \psi_j = 0$ . For this sequence and for arbitrary  $R > 0$ , the restrictions  $\psi_j|_{\Omega_R}$  are a Cauchy sequence in  $H^1(\Omega_R)$  by Poincaré's inequality. This implies that  $(\psi_j)_j$  converges to some  $\psi \in H_{\text{loc}}^1(\Omega)$  locally. Since  $(\nabla \psi_j)$  converges in  $L^2(\Omega, \mathbb{C}^3)$  to some  $F$ , there holds  $F = \nabla \psi$  and  $\psi \in \dot{H}^1(\Omega)$ . We conclude that  $G^{(H)}$  is closed as a subspace of  $H(\text{curl}, \Omega)$  and of  $L^2(\Omega, \mathbb{C}^3)$ .

The spaces  $D^{(H)}$  and  $G^{(H)}$  are orthogonal in  $L^2(\Omega, \mathbb{C}^3)$  with the weighted scalar product  $\langle u, v \rangle = \int_{\Omega} \mu u \cdot \bar{v}$  and in  $H(\text{curl}, \Omega)$  with the scalar product  $\langle u, v \rangle = \int_{\Omega} \mu u \cdot \bar{v} + \text{curl } u \cdot \text{curl } \bar{v}$ .

Let  $f_h \in L^2(\Omega)$  satisfy  $\int_{\Omega} f_h \cdot \nabla \psi = 0$  for all  $\psi \in \dot{H}^1(\Omega, \mathbb{C})$ ; this is encoding that  $f_h$  is divergence-free with  $\nu \cdot f_h = 0$  on  $\partial\Omega$ . Since the left hand side of (1.2) vanishes for  $\phi = \nabla \psi \in G^{(H)}$ , we find  $H \in D^{(H)}$ .

The condition  $H \in D^{(H)}$  includes a boundary condition for  $H$ . The fact that  $\mu H$  is  $L^2$ -orthogonal to gradients (without condition on the boundary values of the potential) is the weak form of  $\nabla \cdot (\mu H) = 0$  and  $\nu \cdot (\mu H) = 0$  on  $\partial\Omega$ . Since  $\mu$  is a scalar, we find  $\nu \cdot H = 0$  on  $\partial\Omega$ .

**A.2. The bounded domain  $W$ .** We study now Helmholtz decompositions for the bounded domain  $W = (0, 2\pi) \times S$ , noting that all results remain valid for domains of the form  $W = (r_1, r_2) \times S$ . Here, we are interested in different boundary conditions. In particular, we have to investigate the boundary condition of  $\alpha$ -quasiperiodicity.

For fixed  $\alpha \in \mathbb{R}$ , we use the spaces  $H_{\alpha}(\text{curl}, W)$  and  $H_{0,\alpha}(\text{curl}, W) := \{u \in H_{\alpha}(\text{curl}, W) \mid \nu \times u = 0 \text{ on } (0, 2\pi) \times \partial S\}$ . We are interested in different pairs of function spaces  $(X, Y)$ . The four choices of interest are (a)  $(H(\text{curl}, W), H^1(W))$ , (b)  $(H_0(\text{curl}, W), H_0^1(W))$ , (c)  $(H_{0,\alpha}(\text{curl}, W), H_{0,\alpha}^1(W))$  or (d)  $(H_{\alpha}(\text{curl}, W), H_{\alpha}^1(W))$ . In the following, the weight function  $\rho$  is either  $\varepsilon$  or  $\mu$ . In all these cases, we have the decomposition  $X = D \oplus G$  with

$$\begin{aligned} D &:= \left\{ u \in X \mid \int_W \rho u \cdot \nabla \psi = 0 \text{ for all } \psi \in Y \right\}, \\ G &:= \{u \in X \mid \exists \psi \in Y : u = \nabla \psi\}. \end{aligned}$$

The decomposition is orthogonal with respect to the scalar products  $\langle u, v \rangle = \int_W \rho u \cdot \bar{v}$  in  $L^2(W, \mathbb{C}^3)$  and  $\langle u, v \rangle = \int_W \rho u \cdot \bar{v} + \text{curl } u \cdot \text{curl } \bar{v}$  in  $H(\text{curl}, W)$ . In the following, our aim is to show that, in any of these cases, the space  $D$  is compactly imbedded in  $L^2(W, \mathbb{C}^3)$ .

We start by showing compactness in Case (a).

**Lemma A.1** (Compactness). *Let  $\rho \in L^\infty(W)$  be bounded below by some positive constant. Then the space*

$$D = \left\{ u \in H(\text{curl}, W) \mid \int_W \rho u \cdot \nabla \psi = 0 \text{ for all } \psi \in H^1(W) \right\}$$

is compactly imbedded in  $L^2(W, \mathbb{C}^3)$ .

*Proof. Step 1: The case  $\rho \equiv 1$ .* We first treat the special case  $\rho \equiv 1$ , in which the space of interest is  $D = D_1$  with

$$D_1 := \left\{ u \in H(\text{curl}, W) \mid \int_W u \cdot \nabla \psi = 0 \text{ for all } \psi \in H^1(W) \right\}.$$

Compactness of  $D_1$  can be derived from classical results. Let  $(u_j)_{j \in \mathbb{N}}$  be a bounded sequence in  $H(\text{curl}, W)$  with  $u_j \in D_1$  for every  $j \in \mathbb{N}$ . In particular, the sequence  $\text{curl } u_j$  is bounded in  $L^2(W, \mathbb{C}^3)$ . Because of  $u_j \in D_1$ , there also holds that  $\text{div } u_j = 0$  in  $W$  and  $\nu \cdot u_j = 0$  on  $\partial W$ . The control of  $\text{curl } u_j$  and  $\text{div } u_j$  together with the boundary conditions imply compactness of the sequence  $u_j$  in  $L^2(W, \mathbb{C}^3)$  by Theorem 3.47 of [23]. Compare also Theorem 3.1 of [24]. This shows compactness of  $D_1$  in  $H(\text{curl}, W)$ .

*Step 2: The general case.* We now consider a general coefficient  $\rho \in L^\infty(W)$  and use further Helmholtz decompositions. Just as  $D$  and  $G$  are defined as subspaces of  $X$ , we can analogously define subspaces in  $L^2(W, \mathbb{C}^3)$ ,

$$\begin{aligned} D_{L^2} &:= \left\{ u \in L^2(W, \mathbb{C}^3) \mid \int_W \rho u \cdot \nabla \psi = 0 \text{ for all } \psi \in H^1(W) \right\}, \\ G_{L^2} &:= \left\{ v \in L^2(W, \mathbb{C}^3) \mid \exists \psi \in H^1(W) : v = \nabla \psi \right\}. \end{aligned}$$

These are closed subspaces of  $L^2(W, \mathbb{C}^3)$ . We observe that  $D_{L^2}$  is the orthogonal complement of  $G_{L^2}$  with respect to the ( $\rho$ -dependent) inner product  $\langle \rho u, v \rangle_{L^2(W)}$  in  $L^2(W, \mathbb{C}^3)$ . It is important to observe that the  $\rho$ -dependent norms in  $H_\alpha(\text{curl}, W)$  and  $L^2(W, \mathbb{C}^3)$  are equivalent to the norms for  $\rho \equiv 1$ .

We will use the two different decompositions as orthogonal direct sums:  $X = D \oplus G$  and

$$L^2(W, \mathbb{C}^3) = D_{L^2} \oplus G_{L^2}.$$

All corresponding projections are bounded; the boundedness of a projection is independent of the choice of the scalar product (with or without the factor  $\rho$ ).

In order to show compactness, we consider once more a bounded sequence  $(u_j)_{j \in \mathbb{N}}$  in  $H(\text{curl}, W)$  with  $u_j \in D$  for every  $j \in \mathbb{N}$ . We decompose  $u_j$  with respect to the decomposition that corresponds to  $\rho = 1$ , that is, using  $H(\text{curl}, W) = D_1 \oplus G$ , where  $H(\text{curl}, W)$  is equipped with the scalar product related to  $\rho = 1$ :

$$u_j = v_j + \nabla \psi_j \quad \text{with } v_j \in D_1 \text{ and } \psi_j \in H^1(W, \mathbb{C}).$$

Since  $u_j$  is bounded in  $H(\text{curl}, W)$  and since projections are bounded, the sequence  $v_j \in D_1$  is bounded in  $H(\text{curl}, W)$ . Step 1 yields that there exists a subsequence,

again denoted by  $v_j$ , which converges in  $L^2(W, \mathbb{C}^3)$ . With this knowledge, we now read the previous decomposition in the form

$$v_j = u_j - \nabla\psi_j,$$

and note that this is a decomposition of  $v_j$  in  $L^2(W, \mathbb{C}^3) = D_{L^2} \oplus G_{L^2}$ ; we exploit here that  $D$  is contained in  $D_{L^2}$ . Since  $v_j$  converges in  $L^2(W, \mathbb{C}^3)$  and since the projection onto  $D_{L^2}$  is bounded in the space  $L^2(W, \mathbb{C}^3)$ , we conclude that  $u_j$  converges in  $L^2(W, \mathbb{C}^3)$ . This concludes the proof.  $\square$

The choice of function spaces that was given as (b) can be treated with exactly the same arguments. We obtain that the space

$$\left\{ u \in H_0(\text{curl}, W) \left| \int_W \rho u \cdot \nabla\psi = 0 \text{ for all } \psi \in H_0^1(W) \right. \right\}$$

is compactly imbedded in  $L^2(W, \mathbb{C}^3)$ .

Our next aim is to generalize these result. Instead of demanding  $\text{div}(\rho u) = 0$ , we want to impose only a boundedness property.

**Lemma A.2** (Improved compactness). *Let  $\rho \in L^\infty(W)$  be real with positive lower bound. Let  $(u_j)_j$  be a bounded sequence in  $X = H(\text{curl}, W)$  such that, for a sequence  $(f_j)_j$  that is bounded in  $L^2(W)$ , there holds*

$$(A.1) \quad \int_W \rho u_j \cdot \nabla\varphi = \int_W f_j \varphi$$

for every  $\varphi \in Y = H^1(W)$ . Then there exists a subsequence  $j \rightarrow \infty$  and a limit function  $u$  such that  $u_j \rightarrow u$  in  $L^2(W, \mathbb{C}^3)$ .

The result remains valid for other pairs  $(X, Y)$ , e.g.: (b)  $(H_0(\text{curl}, W), H_0^1(W))$ , (c)  $(H_{0,\alpha}(\text{curl}, W), H_{0,\alpha}^1(W))$ , (d)  $(H_\alpha(\text{curl}, W), H_\alpha^1(W))$ .

*Proof.* On the two spaces  $H(\text{curl}, W)$  and  $L^2(W, \mathbb{C}^3)$  we define again inner products  $\int_W \text{curl} u \cdot \text{curl} \bar{v} + \rho u \cdot \bar{v}$  and  $\int_W \rho u \cdot \bar{v}$ , respectively. Using the decomposition  $H(\text{curl}, W) = G \oplus D$  we decompose  $u_j$  as

$$u_j = v_j + \nabla\psi_j \quad \text{with } v_j \in D \text{ and } \psi_j \in H^1(W).$$

Since  $v_j$  is obtained as a projection of  $u_j$ , the sequence  $v_j$  is bounded in  $H(\text{curl}, W)$ . Additionally, the sequence lies in  $D$ . Lemma A.1 provided the compactness of the subspace  $D$ , hence we find a subsequence  $j \rightarrow \infty$  and a limit function  $v$  such that  $v_j \rightarrow v$  in  $L^2(W, \mathbb{C}^3)$ .

The functions  $\psi_j \in H^1(W)$  solve the problem

$$\int_W \rho \nabla\psi_j \cdot \nabla\varphi = \int_W \rho (u_j - v_j) \cdot \nabla\varphi = \int_W f_j \varphi \quad \text{for all } \varphi \in H^1(W).$$

We consider the solution operator  $f_j \mapsto \nabla\psi_j$  of this problem. By the Lax-Milgram lemma, the solution operator is a bounded operator  $(H^1(W))' \rightarrow L^2(W, \mathbb{C}^3)$  on the dual space  $(H^1(W))'$  of  $H^1(W)$ . As  $H^1(W)$  is compactly imbedded in  $L^2(W)$ , the embedding  $L^2(W) \rightarrow (H^1(W))'$  is also compact. This compactness allows to choose a subsequence  $j \rightarrow \infty$  and a limit function  $f \in L^2(W, \mathbb{C}^3)$  such that  $f_j \rightarrow f$  is a strong convergence in  $(H^1(W))'$ . The corresponding solutions  $\nabla\psi_j$  are then strongly convergent in  $L^2(W, \mathbb{C}^3)$ .

The strong convergences of  $v_j$  and  $\nabla\psi_j$  imply the strong convergence of  $u_j$ . This concludes the proof in the case  $(X, Y) = (H(\text{curl}, W), H^1(W, \mathbb{C}))$ .

In the case  $(X, Y) = (H_0(\text{curl}, W), H_0^1(W))$ , the above proof remains valid by the remark following the preceding lemma. The cases of functions spaces involving quasiperiodic boundary conditions at the flat boundaries  $\{0\} \times S$  and  $\{2\pi\} \times S$  can be reduced to the cases of homogeneous boundary conditions by choosing a function  $\eta \in C^\infty(\mathbb{R})$  with  $\eta(x_1) = 1$  for  $x_1 \in [0, 2\pi]$  and  $\eta(x_1) = 0$  for  $x_1 \notin [-1, 2\pi + 1]$  and applying this result to  $\tilde{u}_j(x) = \eta(x_1)u_j(x)$ .  $\square$

For use in Appendix B, we formulate the following special case of our results.

**Corollary A.3.** *Let  $\mu \in L^\infty(W)$  be bounded below by some positive constant and let  $\alpha \in [-1/2, 1/2]$  be a quasimoment. Then the space*

$$\left\{ u \in H_\alpha(\text{curl}, W) \mid \int_W \mu u \cdot \nabla \psi = 0 \text{ for all } \psi \in H_\alpha^1(W) \right\}$$

*is compactly imbedded in  $L^2(W, \mathbb{C}^3)$ .*

## APPENDIX B. PROPERTIES OF THE OPERATOR $\text{curl curl}$

In this appendix, we study an operator on a space of  $\alpha$ -quasiperiodic functions. The parameter  $\alpha \in I$  is fixed throughout this appendix and any dependence on  $\alpha$  is suppressed. Correspondingly, for notational convenience, we suppress the tilde that was used in (2.11) and write  $L$  instead of  $\tilde{L}_\alpha$ . In this appendix, we study the space  $H_\alpha(\text{curl}, W)$ , equipped with the scalar product

$$(B.1) \quad \langle u, \varphi \rangle_{H(\text{curl}, W)} = \int_W \left\{ \frac{1}{\varepsilon} \text{curl } u \cdot \text{curl } \bar{\varphi} + \mu u \cdot \bar{\varphi} \right\},$$

and the operator  $L : H_\alpha(\text{curl}, W) \rightarrow H_\alpha(\text{curl}, W)$ , defined by

$$(B.2) \quad \langle Lu, \varphi \rangle_{H(\text{curl}, W)} = \int_W \left\{ \frac{1}{\varepsilon} \text{curl } u \cdot \text{curl } \bar{\varphi} - \omega^2 \mu u \cdot \bar{\varphi} \right\}$$

for all  $u, \varphi \in H_\alpha(\text{curl}, W)$ . As above,  $W = (0, 2\pi) \times S$  and  $\varepsilon, \mu \in L^\infty(\Omega)$  are real valued and have a positive lower bound.

The previous subsection provides with case (d) the Helmholtz decomposition  $H_\alpha(\text{curl}, W) = D \oplus G$  with

$$\begin{aligned} D &= \left\{ u \in H_\alpha(\text{curl}, W) \mid \int_W \mu u \cdot \nabla \psi = 0 \text{ for all } \psi \in H_\alpha^1(W) \right\}, \\ G &= \left\{ v \in H_\alpha(\text{curl}, W) \mid \exists \psi \in H_\alpha^1(W) : v = \nabla \psi \right\}. \end{aligned}$$

The subspace  $D$  is the  $H(\text{curl}, W)$ -orthogonal complement of  $G$ .

**Lemma B.1** (Fredholm property). *The operator  $L$  is a self-adjoint Fredholm operator with index 0.*

*Proof.* The definition of  $L$  in (B.2) is symmetric, this implies that  $L$  is self-adjoint.

*Step 1: Expressing  $L$  in the decomposition  $H_\alpha(\text{curl}, W) = D \oplus G$ .* We claim that  $Lu \in D$  holds for every  $u \in D$ . This follows when we show that  $Lu$  is orthogonal to  $G$ . Let therefore  $v = \nabla \psi \in G$  be arbitrary. We calculate

$$\langle Lu, v \rangle_{H(\text{curl}, W)} = \langle Lu, \nabla \psi \rangle_{H(\text{curl}, W)} = -\omega^2 \langle \mu u, \nabla \psi \rangle_{L^2(W)} = 0,$$

using the definition of  $D$ . This shows  $L|_D : D \rightarrow D$ . The same calculation can be performed for  $G$ : Let  $v \in G$  be arbitrary, we consider  $Lv \in X$  and a test-function  $u \in D$  to calculate

$$\langle Lv, u \rangle_{H(\text{curl}, W)} = -\omega^2 \langle \mu v, u \rangle_{L^2(W)} = -\omega^2 \langle v, \mu u \rangle_{L^2(W)} = 0,$$

where we exploited that  $\mu$  is real. This shows  $L|_G : G \rightarrow G$ . We can therefore write  $L$  on the space  $H_\alpha(\text{curl}, W) = D \oplus G$  in the form

$$(B.3) \quad L = \begin{pmatrix} L|_D & 0 \\ 0 & L|_G \end{pmatrix}.$$

*Step 2: Fredholm property of  $L|_D$ .* We claim that  $L|_D : D \rightarrow D$  is a Fredholm operator with index 0. To prove this, we show a stronger property, namely that  $K := L - \text{id}$  is a compact operator  $D \rightarrow D$ . The equation  $Ku = F$  is equivalent to  $Lu = u + F$ , which can be written as

$$\langle Lu, \varphi \rangle_{H(\text{curl}, W)} = \langle u, \varphi \rangle_{H(\text{curl}, W)} + \langle F, \varphi \rangle_{H(\text{curl}, W)} \quad \text{for all } \varphi \in H_\alpha(\text{curl}, W).$$

This, by definition of  $L$ , is equivalent to

$$\int_W \frac{1}{\varepsilon} \text{curl } u \cdot \text{curl } \bar{\varphi} - \omega^2 \mu u \cdot \bar{\varphi} = \int_W \frac{1}{\varepsilon} \text{curl } u \cdot \text{curl } \bar{\varphi} + \mu u \cdot \bar{\varphi} + \langle F, \varphi \rangle_{H(\text{curl}, W)}$$

for all  $\varphi \in H_\alpha(\text{curl}, W)$ , and hence also equivalent to

$$(B.4) \quad \int_W \mu (1 + \omega^2) u \cdot \bar{\varphi} = -\langle F, \varphi \rangle_{H(\text{curl}, W)} \quad \text{for all } \varphi \in H_\alpha(\text{curl}, W).$$

In order to show compactness of  $K$ , we consider a bounded sequence  $u_j \in D$  and the images  $F_j := Ku_j$ . Corollary A.3 provides compactness of  $D$  in  $L^2(W, \mathbb{C}^3)$ , hence, up to the choice of a subsequence (not relabeled), we can assume  $u_j \rightarrow u$  in  $L^2(W, \mathbb{C}^3)$ . Because of (B.4), the sequence  $F_j$  consists of the Riesz representations of  $\langle -\mu(1 + \omega^2) u_j, \cdot \rangle_{L^2(W)}$  in  $H(\text{curl}, W)$ . This implies the convergence  $F_j \rightarrow F$  in  $H(\text{curl}, W)$ . Since we have found a convergent subsequence of the images  $F_j$ , we have verified the compactness of  $K$ .

*Step 3: Fredholm property of  $L|_G$ .* Let us investigate the action of  $L$  on the subspace  $G$ . We consider  $Lu = F$  with  $u \in G$  and, hence,  $F \in G$ . The equation is reads  $\langle Lu, \varphi \rangle_{H(\text{curl}, W)} = \langle F, \varphi \rangle_{H(\text{curl}, W)}$  for every  $\varphi \in H_\alpha(W)$ . By definition of  $L$  and by definition of the scalar product on  $H(\text{curl}, W)$ , this is equivalent to  $-\int_W \omega^2 \mu u \cdot \bar{\varphi} = \int_W \mu F \cdot \bar{\varphi}$ . We find that, on  $G$ , the operator  $L$  is nothing but the multiplication  $u \mapsto -\omega^2 u$ . This operator has a continuous inverse and is therefore a Fredholm operator with index 0.

Step 2 and Step 3 imply that  $L$  is Fredholm with index 0.  $\square$

### APPENDIX C. DECAY OF SOLUTIONS TO THE POISSON PROBLEM

The subsequent lemma is a very general statement about solutions of Poisson problems in unbounded cylindrical domains. In this appendix, we only assume the following: The dimension is  $d \geq 2$ , the set  $S \subset \mathbb{R}^{d-1}$  is a bounded Lipschitz domain, the unbounded domain is  $\Omega = \mathbb{R} \times S$ , the coefficient is a map  $\rho : \Omega \rightarrow \mathbb{R}$  of class  $L^\infty(\Omega)$  with a positive lower bound. In particular, we do not assume that  $\rho$  is periodic in direction  $x_1$ .

In our results on compactly perturbed media, we use the lemma with the coefficient function  $\rho$  being the permittivity  $\varepsilon$  or the permeability  $\mu$ . For shorter formulas, we use here segments of unit length instead of segments of length  $2\pi$ .

**Lemma C.1** (Decay of Poisson solutions). *Let  $\rho : \Omega \rightarrow \mathbb{R}$  be of class  $L^\infty(\Omega)$  with a positive lower bound. Let  $R > 0$  be fixed, we consider right hand sides  $g$  that are supported in  $\Omega_R = (-R, R) \times S$ . For arbitrary  $r > 0$  let  $W_r$  be the segment  $W_r = (r, r+1) \times S$ . Then there exists a constant  $C = C(\rho, R)$  and a decay rate*

$\delta = \delta(\rho, R)$  such that, for every function  $g : \Omega \rightarrow \mathbb{C}$  that is supported in  $\Omega_R$ , the following two properties holds:

**Dirichlet problem:** Every solution  $v \in H_0^1(\Omega, \mathbb{C})$  of

$$(C.1) \quad \int_{\Omega} \rho \nabla v \cdot \nabla \bar{\varphi} = \int_{\Omega} g \cdot \nabla \bar{\varphi} \quad \forall \varphi \in H_0^1(\Omega)$$

satisfies the exponential decay estimate:

$$(C.2) \quad \int_{W_r} |\nabla v|^2 \leq C \|g\|_{L^2(\Omega_R)}^2 e^{-\delta|r|} \quad \forall r \in \mathbb{R}.$$

**Neumann problem:** Every solution  $v \in \dot{H}^1(\Omega) := \{v \in L_{\text{loc}}^2(\Omega) | \nabla v \in L^2(\Omega)\}$  of the Neumann problem

$$(C.3) \quad \int_{\Omega} \rho \nabla v \cdot \nabla \bar{\varphi} = \int_{\Omega} g \cdot \nabla \bar{\varphi} \quad \forall \varphi \in \dot{H}^1(\Omega).$$

satisfies the exponential decay estimate (C.2).

*Proof. Step 1: Existence of solutions.* The Dirichlet problem can be solved in standard function spaces with the Lax-Milgram lemma. On the space  $H_0^1(\Omega)$  we use the sesquilinear form  $b(v, \varphi) := \int_{\Omega} \rho \nabla v \cdot \nabla \bar{\varphi}$ . This form is coercive since  $H_0^1(\Omega)$  permits a Poincaré inequality  $\int_{\Omega} |v|^2 \leq C_P \int_{\Omega} |\nabla v|^2$ . The right hand side of (C.1) defines a linear form on  $\varphi \in H_0^1(\Omega)$ . We find existence and uniqueness of solutions  $v \in H_0^1(\Omega, \mathbb{C})$  together with an estimate  $\|v\|_{H^1(\Omega)} \leq C \|g\|_{L^2(\Omega_R)}$ .

For problem (C.3), one has to modify the function space. We use the space  $\dot{H}^1(\Omega) := \{v \in L_{\text{loc}}^2(\Omega, \mathbb{C}) | \nabla v \in L^2(\Omega)\}$  with the squared norm  $\|v\|^2 := \int_{\Omega_R} |v|^2 + \int_{\Omega} |\nabla v|^2$ , and consider once more the sesquilinear form  $b(v, \varphi) := \int_{\Omega} \rho \nabla v \cdot \nabla \bar{\varphi}$ . In order to find a solution  $v$ , we restrict  $b$  to a closed subspace of  $\dot{H}^1(\Omega)$ , namely to  $\dot{H}_*^1(\Omega) := \left\{ v \in \dot{H}^1(\Omega) \mid \int_{\Omega_R} v = 0 \right\}$ . The Poincaré inequality on  $\Omega_R$  for vanishing averages of  $u$  implies that  $b$  is coercive on  $\dot{H}_*^1(\Omega)$ ; the Lax-Milgram lemma yields a solution  $v \in \dot{H}_*^1(\Omega)$  of

$$(C.4) \quad b(v, \psi) = \int_{\Omega} g \cdot \nabla \psi \quad \text{for all } \psi \in \dot{H}_*^1(\Omega).$$

An arbitrary function  $\varphi \in \dot{H}^1(\Omega)$  can be decomposed, for some constant  $c \in \mathbb{C}$ , as  $\varphi = c + \psi$  with  $\psi \in \dot{H}_*^1(\Omega)$ . This allows to check (C.3): For arbitrary  $\varphi = c + \psi \in \dot{H}^1(\Omega)$  with  $\psi \in \dot{H}_*^1(\Omega)$  holds

$$\int_{\Omega} \rho \nabla v \cdot \nabla \varphi = \int_{\Omega} \rho \nabla v \cdot \nabla \psi = b(v, \psi) = \int_{\Omega} g \cdot \nabla \bar{\psi} = \int_{\Omega} g \cdot \nabla \bar{\varphi}.$$

Lax-Milgram yields also the uniqueness of  $\nabla v$  and, hence, uniqueness up to constants of  $v$ . We emphasize that, in general,  $v$  will not be of class  $L^2(\Omega)$ , for any choice of the constant.

*Step 2: Exponential decay for the Dirichlet problem.* We consider a solution  $v \in H_0^1(\Omega)$  of (C.1). All constants in this proof will be independent of  $v$  and  $g$ , they depend on  $\rho$  only through the upper and lower bounds of  $\rho$ .

For arbitrary  $r > 0$ , we use the domain  $\Sigma_r := (r, \infty) \times S \subset \Omega$ . We perform all arguments for  $r > 0$ , the arguments for  $r < 0$  are analogous.

We note that the test-function  $\varphi = v$  leads to the equality  $\int_{\Omega} \rho |\nabla v|^2 = \int_{\Omega} g \cdot \nabla \bar{v}$ . We now modify the test-function and construct  $\varphi$  as follows:  $\varphi(x) := v(x)$  for  $x_1 < r$ ,  $\varphi(x) := v(x)(r+1-x_1)$  for  $r \leq x_1 \leq r+1$ ,  $\varphi(x) := 0$  for  $x_1 > r+1$ . The definition

implies  $\varphi \in H_0^1(\Omega)$ , hence  $\varphi$  is an admissible test-function. For  $r > R$  we find, using that the support of  $g$  is contained in  $\Omega_R$ ,

$$\begin{aligned} \int_{\Omega} \rho |\nabla v|^2 &= \int_{\Omega} g \cdot \nabla \bar{v} = \int_{\Omega} g \cdot \nabla \bar{\varphi} = \int_{\Omega} \rho \nabla v \cdot \nabla \bar{\varphi} \\ &= \int_{\Omega \setminus \Sigma_r} \rho |\nabla v|^2 + \int_{W_r} \rho \nabla v \cdot [(\nabla \bar{v})(r+1-x_1) - \bar{v} e_1]. \end{aligned}$$

Subtracting the first term of the right hand side, and using a Poincaré inequality for the last integral, we find

$$(C.5) \quad \int_{\Sigma_r} \rho |\nabla v|^2 \leq C \int_{W_r} \rho |\nabla v|^2.$$

The constant  $C > 1$  is independent of  $r$ , it is a consequence of the Poincaré inequality  $\|v\|_{L^2(W_r)} \leq C_P \|\nabla v\|_{L^2(W_r)}$  for all  $v \in H_0^1(\Omega)$ . Inequality (C.5) allows to calculate

$$(C.6) \quad \int_{\Sigma_{r+1}} \rho |\nabla v|^2 = \int_{\Sigma_r} \rho |\nabla v|^2 - \int_{W_r} \rho |\nabla v|^2 \leq \left(1 - \frac{1}{C}\right) \int_{\Sigma_r} \rho |\nabla v|^2.$$

This implies, in particular, the exponential decay (C.2).

*Step 3: Exponential decay for the Neumann problem.* We follow the ideas of Step 2 and consider the solution  $v \in \dot{H}^1(\Omega)$  of (C.3). Without loss of generality, subtracting a constant, we can assume  $v \in \dot{H}_*^1(\Omega)$ ; this means that we work with the solution  $v$  that was found by solving (C.4).

For  $r > R$ , we consider the average  $c_r := \frac{1}{|W_r|} \int_{W_r} v$  of the function  $v$  in  $W_r$  and define

$$\varphi(x) := \begin{cases} v(x) & \text{for } x_1 \leq r, \\ c_r + (v(x) - c_r)(r+1-x_1) & \text{for } r \leq x_1 \leq r+1, \\ c_r & \text{for } x_1 > r+1. \end{cases}$$

We note that, for  $x_1 = r$ , the expression in the middle coincides with  $v$ , while, for  $x_1 = r+1$ , the expression in the middle coincides with  $c_r$ . In particular, there holds  $\varphi \in \dot{H}^1(\Omega)$ .

Repeating the first calculation of Step 2 yields

$$\int_{\Sigma_r} \rho |\nabla v|^2 = \int_{W_r} \rho \nabla v \cdot [(\nabla \bar{v})(r+1-x_1) - (\bar{v} - \bar{c}_r) e_1].$$

The constant  $c_r$  is chosen such that  $\int_{W_r} (v - c_r) = 0$ . This allows to use a Poincaré inequality on  $W_r$ : There exists  $C_P > 0$  with  $\|\tilde{v}\|_{L^2(W_r)} \leq C_P \|\nabla \tilde{v}\|_{L^2(W_0)}$  for all  $\tilde{v} \in H^1(W_r)$  with  $\int_{W_r} \tilde{v} = 0$ , the constant  $C_P$  is independent of  $r$ . Using this inequality for  $\tilde{v} = v - c_r$ , we obtain

$$\int_{\Sigma_r} \rho |\nabla v|^2 \leq C \int_{W_r} \rho |\nabla v|^2$$

with  $C$  independent of  $g$ ,  $v$ , and  $r$ . We have thus obtained (C.5) also in the Neumann case and the exponential decay follows as in Step 2.  $\square$

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