American Journal of Physics

PAPERS | SEPTEMBER 01 2022

The basic concepts determining electromagnetic shielding

Guy A. E. Vandenbosch

Check for updates

Am. J. Phys. 90, 672–681 (2022)
https://doi.org/10.1119/5.0087295

View Online
Export Citation

04 August 2024 09:01:49

The basic concepts determining electromagnetic shielding

Guy A. E. Vandenbosch[a)]
Department of Electrical Engineering, Katholieke Universiteit Leuven, Kasteelpark Arenberg 10, 3001 Leuven, Belgium

(Received 3 February 2022; accepted 28 June 2022)

Shielding involves much more than just putting a conductive screen in between an emitting source and a susceptible device. Starting from Maxwell's equations, the concept of electromagnetic shielding is formally explained. The physical working mechanisms behind the two basic forms of shielding, electric field and magnetic field shielding, are given, and the link between them at higher frequencies is clarified. Several aspects, like the effect of gridding or weaving a shield, the effect of the finite size of a shield, and the penetration through the metal of a shield, are discussed based on very simple canonical shielding topologies that can be solved analytically. Although the classical paradigm to explain shielding based on the notions of skin depth and eddy current is not followed, conceptual links with this classical paradigm are explained. © *2022 Published under an exclusive license by American Association of Physics Teachers.*

https://doi.org/10.1119/5.0087295

04 August 2024 09:01:49

I. INTRODUCTION

In the minds of most scientists and engineers, electromagnetic shielding involves putting an electromagnetic screen, i.e., a shield, between a source of electromagnetic waves and a susceptible device. This technique is widespread among experimentalists, technicians, and designers of equipment and measurement setups. Electromagnetic shielding is also important in life outside of the laboratory. For example, the steel reinforcement of concrete walls and floors partially shields the inside of buildings from the mobile phone wireless networks deployed outside, which explains the typically lower signal level indoors. Also, shielding is one of the most basic drivers of the EMC industry.[1,2] EMC (ElectroMagnetic Compatibility) is the study of the simultaneous functioning of electric and/or electronic devices in each other's neighborhood.

Electromagnetic shielding is commonly taught in physics and engineering curricula. At higher frequencies, the concept of both electric and magnetic shielding is often explained starting from the configuration involving a plane wave incident on a metal screen.[3,4] In some cases, this may lead to incorrect interpretations as pointed out by Fahy *et al*.[5] Solving Maxwell's equations for this simple geometry yields the coefficients of reflection and transmission. It is easily shown that for good metal screens, the reflection is very high, and the transmission is very low, leading to good shielding properties. Although this approach is educationally sensible, unfortunately it does not give the student a thorough understanding of many aspects that are crucial in the practical application of shielding when designing electronic systems. In the simple "plane wave understanding" of shielding, many questions are completely left unanswered. Questions as "Is there a difference in behavior of a screen at low and high frequencies?," "Does shielding work only for two-dimensional screens?," "How large is the spatial zone shielded by a screen?," "Is electric and magnetic shielding always the same, as in this simple plane wave case?" cannot be answered based solely on the plane wave explanation.

At lower frequencies, the concept of eddy currents is used mainly to explain magnetic shielding.[6] Eddy currents are electric currents flowing in loops within conductors due to a changing magnetic field in the conductors. They are governed by Faraday's law of induction. Shielding is then based on the fact that this current swirls in such a way as to create an induced magnetic field that opposes the phenomenon that created it, resulting in a certain level of magnetic shielding. For the novice, this low-frequency paradigm invokes other questions: "Does this mechanism also generate electric shielding?," "What is the relation between the incident and reflected (plane) wave description and the eddy current description?," etc.

The result is that the novice physicist or engineer who is confronted with an electromagnetic interference problem may just try to put "some" screen in between the source and the "problematic" device in the hope that the field levels will be reduced sufficiently in order to solve the problem.

In this paper, the basic working mechanisms of electromagnetic shielding are explained based on the laws of electromagnetism. The presentation is completely different from what is traditionally taught and leads to a much more robust understanding of the basic phenomena involved. The approach followed in this paper allows correct assessment of many practical situations: Those where shielding is already occurring or where it has to be applied in order to solve a practical interference problem. Shielding geometries that are discussed include conducting wires, woven shields, and solid screens, and both penetration through and diffraction around shields are considered. Concrete calculations are based on very simple topologies that can be solved analytically: the simple straight wire, a raster of parallel straight wires, and a conducting half plane. To the knowledge of the author, the paradigm followed in this paper has never been published before. Most didactic papers on the topic consider electrostatic cases only.[7–9] However, electrostatic shielding is not as important in daily life compared to screening of non-zero frequency fields. Readers looking for more advanced treatments of practical shielding problems may wish to consult the *IEEE Transactions on Electromagnetic Compatibility*.[10,11]

II. THE BASIC EQUATIONS

All electromagnetic phenomena can be described by Maxwell's laws, expressed in the vector fields **E** (electric field) and **B** (magnetic field). In general, these fields depend on the coordinates (x, y, z) and on time t. For simplicity, these dependencies are not explicitly mentioned further. In time-harmonic situations (i.e., in the frequency domain with the time-harmonic convention $e^{j\omega t}$) and in integral form, these equations are

$$\oint_c \mathbf{E} \cdot d\mathbf{C} = -j\omega \iint_S \mathbf{B} \cdot d\mathbf{S}, \tag{1}$$

$$\begin{aligned}\oint_c \mathbf{B} \cdot d\mathbf{C} &= j\omega \iint_S \varepsilon\mu\mathbf{E} \cdot d\mathbf{S} + \iint_S \mu(\mathbf{J}^{ind} + \mathbf{J}^{so}) \cdot d\mathbf{S} \\ &= \iint_S (j\omega\varepsilon + \sigma)\mu\mathbf{E} \cdot d\mathbf{S} + \iint_S \mu\mathbf{J}^{so} \cdot d\mathbf{S},\end{aligned} \tag{2}$$

where S is an arbitrary surface in space and C its contour. Here, $\mathbf{J} = \mathbf{J}^{ind} + \mathbf{J}^{so}$ is the electric volume current density, which is also a vector field depending on (x, y, z), and which can be written as the sum of an imposed source current $\mathbf{J}^{so}$, typically a current source injecting current into the system, and a current $\mathbf{J}^{ind} = \sigma\mathbf{E}$, the Ohmic current density induced by the electric field in the conductor. The fields are, thus, "generated" by the source current $\mathbf{J}^{so}$. The materials are assumed to be linear, homogenous, isotropic, and time-invariant and have permittivity (ε), permeability (μ), and conductivity (σ) that are frequency independent in the frequency band considered. Note that in (1) and (2), the permittivity, permeability, and conductivity are scalar functions that may vary over space, which means that they have to stay part of the integrands. The result is that these expressions can be applied without modification, even when crossing material boundaries. The differential form of Maxwell's equations for the considered materials is

$$\nabla \times \mathbf{E} = -j\omega\mathbf{B}, \tag{3}$$

$$\nabla \times \mathbf{B} = (j\omega\varepsilon + \sigma)\mu\mathbf{E} + \mu\mathbf{J}^{so}. \tag{4}$$

III. SHIELDING EFFECTIVENESS

Traditionally, the quality of shielding is expressed with the parameter shielding effectiveness (SE). It is the ratio of the field in the absence of the shield (also called the incident field) to the field in the presence of the shield

$$\mathrm{SE}\,(\mathrm{dB}) = 20\log_{10}[\mathrm{SE}\,(\mathrm{linear})] = 20\log_{10}\left|\frac{\mathbf{F}_{inc}}{\mathbf{F}_{sh}}\right|, \tag{5}$$

where $\mathbf{F}$ is the field. This parameter can be defined both for the electric field (electric shielding, $\mathbf{F} = \mathbf{E}$) and the magnetic field (magnetic shielding, $\mathbf{F} = \mathbf{B}$).

IV. ELECTRIC SHIELDING

The line of reasoning for electric shielding, i.e., shielding of the electric field, starts with Ohm's law

$$\mathbf{J}^{ind} = \sigma\mathbf{E}, \tag{6}$$

which leads to a time-averaged dissipated power density in the conductor of

$$p_{loss} = \frac{1}{2}\mathbf{E} \cdot \mathbf{J}^{ind} = \frac{\sigma|\mathbf{E}|^2}{2}. \tag{7}$$

Since energy and power quantities have to stay finite, in the limit that the conductivity goes to infinity, the electric field has to go to zero. This leads to the well-known result that in a perfect conductor, the electric field is zero, and inside a shield with very large conductivity, the electric field is nearly zero.

The second step in the line of reasoning relates the fields inside the shield to the fields just outside the shield. Applying Faraday's law (1) to the geometry in Fig. 1 for a height dh and a length dl in the limit both going to zero, we obtain

$$(E_{1t} - E_{2t})dl = -j\omega d\phi = -j\omega\left(B_{1t}dl\frac{dh}{2} + B_{2t}dl\frac{dh}{2}\right), \tag{8}$$

where E_{it} is the component of the electric field parallel to dl in region $i = 1, 2$ and B_{it} is the component of the magnetic field also tangential to this surface and simultaneously normal to the loop. For a vanishing dh, the magnetic flux $d\phi$ through the elementary surface is vanishing. It follows that the electric field tangential to and just outside the shield is the same as this field just inside, which is nearly zero. The practical result is that a shield indeed makes the electric field tangential to it very small just outside the shield.

It is very important to emphasize that the previous line of reasoning does not involve frequency. For real-life conductors with large but finite conductivity, electric shielding works down to zero frequency, i.e., DC.

It is also important to emphasize that this line of reasoning can be applied not only in the case of a screen, i.e., a two-dimensional shield, but also in the case of a conducting wire, further called a one-dimensional shield. A one-dimensional shield shields its immediate environment from electric field components along its direction.

Note that the notions "in front of" and "behind" the screen are irrelevant for the line of reasoning followed up to now. In principle, a shield shields both just in front of it and just behind it. These notions become important when the actual size of the spatial zone in which the field is shielded is considered. The size of the shielded region depends very much on the exact geometry of the shield and the frequency. The study of a few well-selected canonical cases is ideal to provide a very good physical insight in this matter. In the rest of

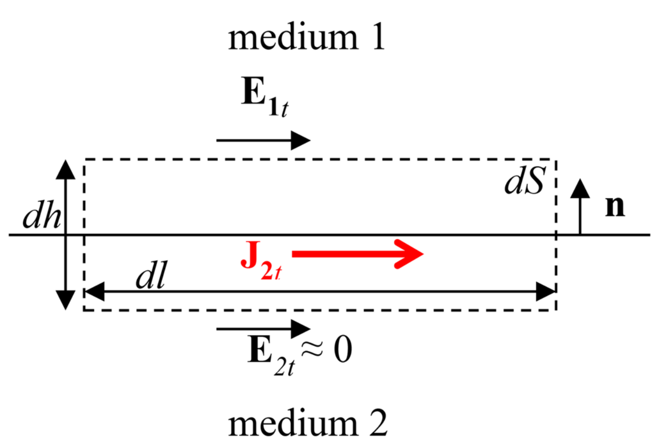


Fig. 1. (Color online) A flat elementary surface dS with length dl and height dh crossing the boundary between a shield (medium 2) and free space (medium 1).

04 August 2024 09:01:49

Sec. III, we will systematically study the size of the zone in space that is shielded. In each section, one specific phenomenon is discussed. Unless specified otherwise, we will only consider cases where the shield consists of perfectly conducting material. This approximation simplifies reasoning without significantly compromising the validity in more general cases.

A. Size of the shielded region for long 1D shields

The first canonical case is a plane wave hitting a very long thin wire of radius a, as in Fig. 2. This case is considered because it clearly illustrates the fact that shielding is not always linked to 2D screens. The direction of incidence is normal to the wire, and the polarization of the incident electric field is parallel with the wire. If the polarization is normal to the wire, there will be no shielding and the plane wave will not be affected.

Note that the shielding problem considered here is fundamentally different from the hollow cylinder problem considered by Aguirregabiria.[12] The problem considered is the shielding at the outside of a wire, not inside a hollow wire (or cylinder), and at arbitrary frequencies, not in the quasi-static limit. We will assume that the wire is very thin, i.e., $ka \ll 1$ with $k = \omega\sqrt{\mu\varepsilon}$ being the wavenumber of the medium in which the wire is embedded (in most cases air or vacuum) and infinitely conducting.

We know already that within the wire, the electric field is zero, and in its immediate neighborhood, the electric field in the direction of the wire is "shielded" and, thus, very small. However, how large is the zone where it is shielded?

We know that the incident plane wave induces a current in the wire. This current generates a so-called scattered field. In the wire, this scattered field compensates the incident field completely, so that the total field becomes zero there. However, it is straightforward to see that due to the cylindrical symmetry, outside the wire this scattered field is actually a cylindrical wave propagating away from the wire. The main component of this scattered wave is analytically known. Outside the wire, it behaves as the Hankel function of second kind and order zero, i.e., $H_0^2(kr)$, with r being the distance from the axis of the wire. The proof is easily given. We start from the source-free Helmholtz wave equation for the electric field

$$\nabla^2\mathbf{E} + k^2\mathbf{E} = 0. \tag{9}$$

Writing in cylindrical coordinates yields

$$\frac{\partial^2\mathbf{E}}{\partial r^2} + \frac{1}{r}\frac{\partial\mathbf{E}}{\partial r} + \frac{1}{r^2}\frac{\partial^2\mathbf{E}}{\partial\varphi^2} + \frac{\partial^2\mathbf{E}}{\partial z^2} + k^2\mathbf{E} = 0. \tag{10}$$

The problem is uniform in the z direction, which means that the derivative with respect to z is zero. The solution can be written as a superposition of sinusoidal modes in the φ direction. For each of these modes, (10) is transformed into the differential equation for the corresponding Bessel functions. The Hankel functions of the first kind can immediately be excluded since they represent waves propagating inward toward the wire from infinity. This is the so-called "radiation boundary condition." This leaves the contributions $(C_{mc}\cos(m\varphi)+C_{ms}\sin(m\varphi))H_m^2(kr)$ with C_{mc} and C_{ms} being unknown coefficients that need to be determined for every mode m. They can be rigorously calculated from the second boundary condition, which states that at the surface of the wire the total z-directed electric field needs to be zero since the wire is perfectly conducting. Projection of this boundary condition onto the separate sinusoidal modes splits this overall equation into equations per mode m that are easily solved. For the zeroth order mode, this equation is

$$\int_0^{2\pi}\left(E_z^{pw}e^{jka\sin\varphi} + C_{0c}H_0^2(ka)\right)d\varphi = 0, \tag{11}$$

so that

$$\begin{aligned} C_{0c} &= \frac{-\int_0^{2\pi} E_z^{pw}e^{jka\sin\varphi}d\varphi}{2\pi H_0^2(ka)} \\ &= \frac{-E_z^{pw}}{\pi H_0^2(ka)}\int_0^{\pi}\cos(ka\sin\varphi)d\varphi \\ &= -E_z^{pw}\frac{J_0(ka)}{H_0^2(ka)}. \end{aligned} \tag{12}$$

For very small wire diameters $ka \ll 1$, only the zeroth order mode gives a non-negligible contribution at distances that are large compared to a. Indeed, all the other modes yield multi-pole like currents flowing within a very small wire cross section, which means that the fields due to the poles of the multi-pole for the largest part cancel each other. The total field a bit further away is, thus, completely formed by the superposition of a plane wave and a cylindrical wave

$$E_z^{total}(r,\varphi) = E_z^{pw}e^{jkr\sin\varphi} + C_{0c}H_0^2(kr). \tag{13}$$

The zone where the electric field can be considered as shielded is determined by the interference patterns between the plane and the cylindrical waves. In Fig. 3, this interference pattern is illustrated along the direction of the plane wave. It is seen that behind the wire, the electric field is marginally reduced over a respectable region. "In front" of the

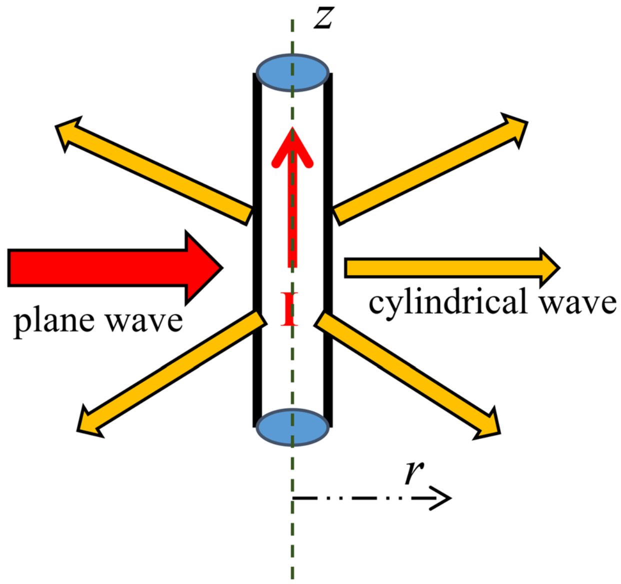


Fig. 2. (Color online) Plane wave hitting a long thin conducting wire. I is the current induced in the wire.

04 August 2024 09:01:49

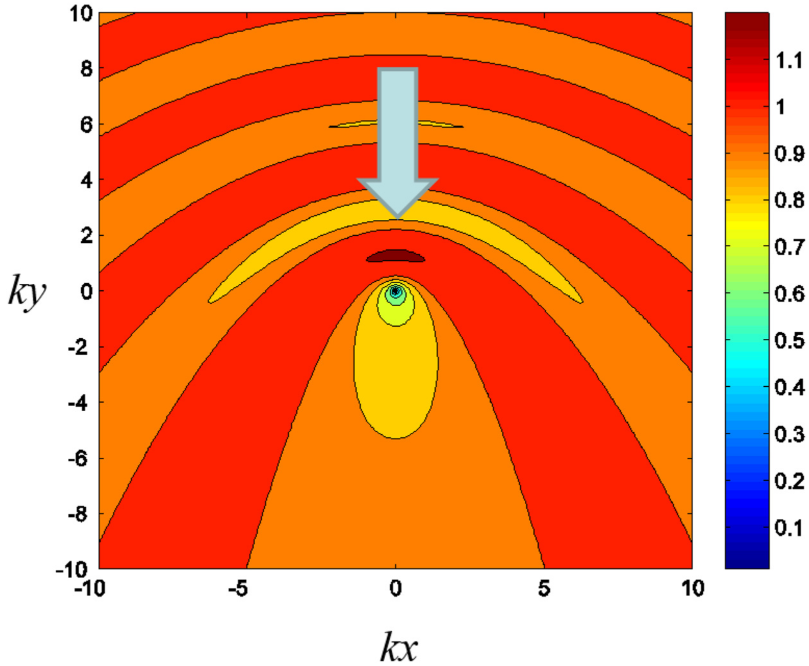


Fig. 3. (Color online) Loci of constant electric field amplitude levels $|\mathbf{E}|$, with $\mathbf{E}$ being the phasor of the sinusoidally time varying electric field. The perfectly conducting wire is located in the origin. The direction of the incident plane wave with amplitude 1 is shown by the blue-grey arrow. The horizontal and vertical axes represent kx and ky, respectively, $k = \omega\sqrt{\mu\varepsilon}$. The radius a of the wire was chosen as $ka = 0.01$. Calculations are performed based on an implementation of Eqs. (12) and (13) in MATLAB (Ref. 13).

wire, this zone is much smaller. There is even a small zone where the field is increased by more than 10%. The physical reason for this is the fact that in front of the wire, the plane wave and the cylindrical wave travel in opposite directions, while behind the wire, they propagate in the same direction, in this way showing a destructive type of interference over a much larger distance. The main conclusion, however, is that considerable shielding is achieved only in the immediate neighborhood of the wire. There, using small argument series expansions for the Bessel functions, the total electric field can be approximated by $E_z^{total}(r) \approx E_z^{pw}(1 - \ln(kr)/\ln(ka))$, which yields a shielding of 90% at $kr \approx (ka)^{0.9} \approx 0.016$ in Fig. 3. At a distance of $\lambda/32$ in the transverse direction, this approximation yields a shielding of only 3.8 dB.

For a wire with finite conductivity σ, the reasoning has to be generalized. For a perfect conductor, all the current is on the surface of the wire, but when the conductivity is finite, the current extends into the bulk of the wire. The outgoing cylindrical wave is generated by a current I induced on the wire by the incident plane wave (as indicated in Fig. 2). Now, the second boundary condition can be obtained by imposing $J = \sigma E_z^{total}$ in the wire. Integrating this equation over the cross section of the wire leads to an equation in terms of the current I. This equation can be solved, and the total field distribution can then be calculated. If the wire radius is much larger than the skin depth, the current is nearly the same as for a perfect conductor, and thus, the shielding is nearly the same. If the wire radius is much smaller than the skin depth, the current density is nearly constant across the wire cross section, but the integrated current is smaller so the shielding is worse. The criterion to have similar shielding properties as for a perfectly conducting wire is, thus, the ratio of skin depth to wire radius. The skin depth is found from $\delta = (2\rho/\omega\mu)^{1/2}$. For copper, $\rho = 1.7 \times 10^{-8}\ \Omega\,\mathrm{m}$ and $\mu \sim \mu_0 = 4\pi \times 10^{-7}\ \mathrm{N/A^2}$, so for a frequency of 1 MHz, $\delta = 0.07$ mm. This means that at a frequency of 1 MHz, copper wire with a radius of 0.5 mm carries a current I that is almost the same as in the case of the perfectly conducting wire and, therefore, has similar shielding properties, but at a frequency of 1 kHz, the shielding will be reduced.

This kind of shielding is seen in printed circuit boards (PCBs), i.e., the green boards that are found in almost any electronic device. Sensitive subsystems are put in the middle of the board, where there is a small shielded zone created by the 1D metal traces near the edges of the PCB.

B. Size of the shielded region for a periodic array of long 1D shields

In many cases, shields are used that do not consist of solid conductive metal but, for example, of gridded or woven metal wires. The darkish glass front of a microwave oven actually contains a gridded shield. At lower frequencies, reinforced concrete in buildings forms a very effective shield thanks to the gridded steel reinforcements. At higher frequencies, it doesn't. The outer conductor of most coaxial cables is actually woven. What is the effect of gridding or weaving and the resulting openings in between the wires?

This phenomenon can be studied in a qualitative way by considering the canonical case of a periodic array of long conductive wires with radius a parallel to each other and with distance d in between, as in Fig. 4. We know already from Sec. IV A that wires only have an effect on an electric field parallel to them, so we will consider a plane wave coming from a direction normal to the plane of the wires and with an electric field polarization parallel to the wires. It is easy to understand that, due to symmetry, the same currents are induced on all the wires. This means that the total field

04 August 2024 09:01:49

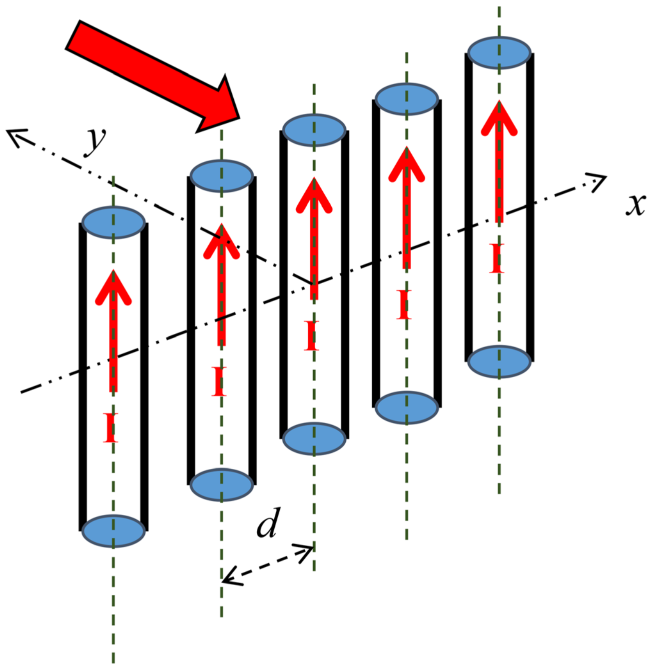


Fig. 4. (Color online) Plane wave hitting a periodic array of infinitely long conducting wires. The distance between two neighboring wires is d. I is the current induced in the wires.

can be written as a superposition of the plane wave and an infinite sum of cylindrical waves, one emanating from each wire, spatially shifted over the proper number of d's.

As long as $a \ll d$, based on the equations for the single wire case, the total field can be written as

$$E_z^{total}(x,y) = E_z^{pw} e^{jky} + \sum_{n=-\infty}^{+\infty} C_{0c} H_0^2\left(k\sqrt{(x-nd)^2 + y^2}\right). \quad (14)$$

If d becomes comparable to a, the current profiles on the wires start to couple so strongly that the reasoning followed further is not valid any more. This case is mathematically much more complex and beyond the scope of this paper.

C_{0c} again needs to be determined from the condition that at the surface of the wires, the total z directed electric field needs to be zero. Following the same projection technique for this zeroth order mode (i.e., integrating this condition over the circumference of the central wire) yields

$$\int_0^{2\pi} E_z^{total}(a\cos\varphi, a\sin\varphi)d\varphi = \int_0^{2\pi}\left(E_z^{pw} e^{jka\sin\varphi} + \sum_{n=-\infty}^{+\infty} C_{0c} H_0^2\left(k\sqrt{(a\cos\varphi - nd)^2 + (a\sin\varphi)^2}\right)\right)d\varphi. \quad (15)$$

As long as $a \ll d$, for $n \neq 0$ the terms under the square root with the factor a can be neglected. For $n = 0$, we obtain the same term as for the single wire. The result is

$$C_{0c} = \frac{-\int_0^{2\pi} E_z^{pw} e^{jka\sin\varphi} d\varphi}{2\pi\left(H_0^2(ka) + 2\sum_{n=1}^{\infty} H_0^2(knd)\right)} = \frac{-E_z^{pw} J_0(ka)}{H_0^2(ka) + 2\sum_{n=1}^{\infty} H_0^2(knd)}. \quad (16)$$

The resulting total field for different d/λ is given in Fig. 5. It is seen that, as expected, the shielding gets better with decreasing values of d/λ. In the limit of very large separations compared to the wavelength (not shown in the figure), the situation is similar to the situation of light rays passing through prison bars. The wave is not stopped at all. From a shielding perspective, the most interesting is to see how the shielding improves drastically below a certain threshold for d/λ. The distance for which a shielding of -6 dB is reached is ca. $d = \lambda/8$. For $d = \lambda/32$, shielding values of ca. -30 dB are reached. This phenomenon is directly related to the fact that for waves with certain wavelength, it is very difficult to pass through openings that are much smaller than their wavelength. The result is a "shielded wave" behind the screen with much smaller amplitude and a standing wave with amplitude nearly twice the incident amplitude in front of the screen. Note, however, that this transmitted amplitude is multiple orders of magnitude larger than the one of a wave actually "penetrating" through the metal of a full metal screen, as will be shown later in this work. Note further that in all cases depicted in Fig. 5, the distance between the wires is much larger than the radius of the wires, so that most of the gridded 2D screen is actually filled with free space. It is not needed to use a lot of metal for shielding purposes; it is just needed to put the metal that is available close enough together compared to the wavelength. Also, note that the field behind the screen very rapidly reaches the plane wave behavior again.

For wires with finite conductivity σ, the reasoning has to be generalized in the same way as for the single wire in Sec. IV A. The outgoing cylindrical waves are generated by currents I induced on the wires by the incident plane wave (as indicated in Fig. 4). Due to symmetry, these currents are identical. The second boundary condition can be obtained by imposing $J = \sigma E_z^{total}$ in one of the wires. Integrating this equation over the cross section of this wire leads to an equation in I. This equation can be solved, and the total field distribution can then be calculated. For a practical copper wire with a radius of 0.5 mm and at normal frequencies (tens of kHz–MHz), again, the shielding properties of the structure turn out to be quite similar.

Note that the conclusions drawn in this section for the wire structure can be generalized to other geometries:

(1) other shapes, for example, strips,
(2) 2D (two dimensional) topologies, such as nets and chicken wire, (the same phenomena occur, but now for both polarizations of the electric field).

Also note that the static version of this problem is considered in the *Feynman Lectures on Physics*.[14] It can be verified

04 August 2024 09:01:49

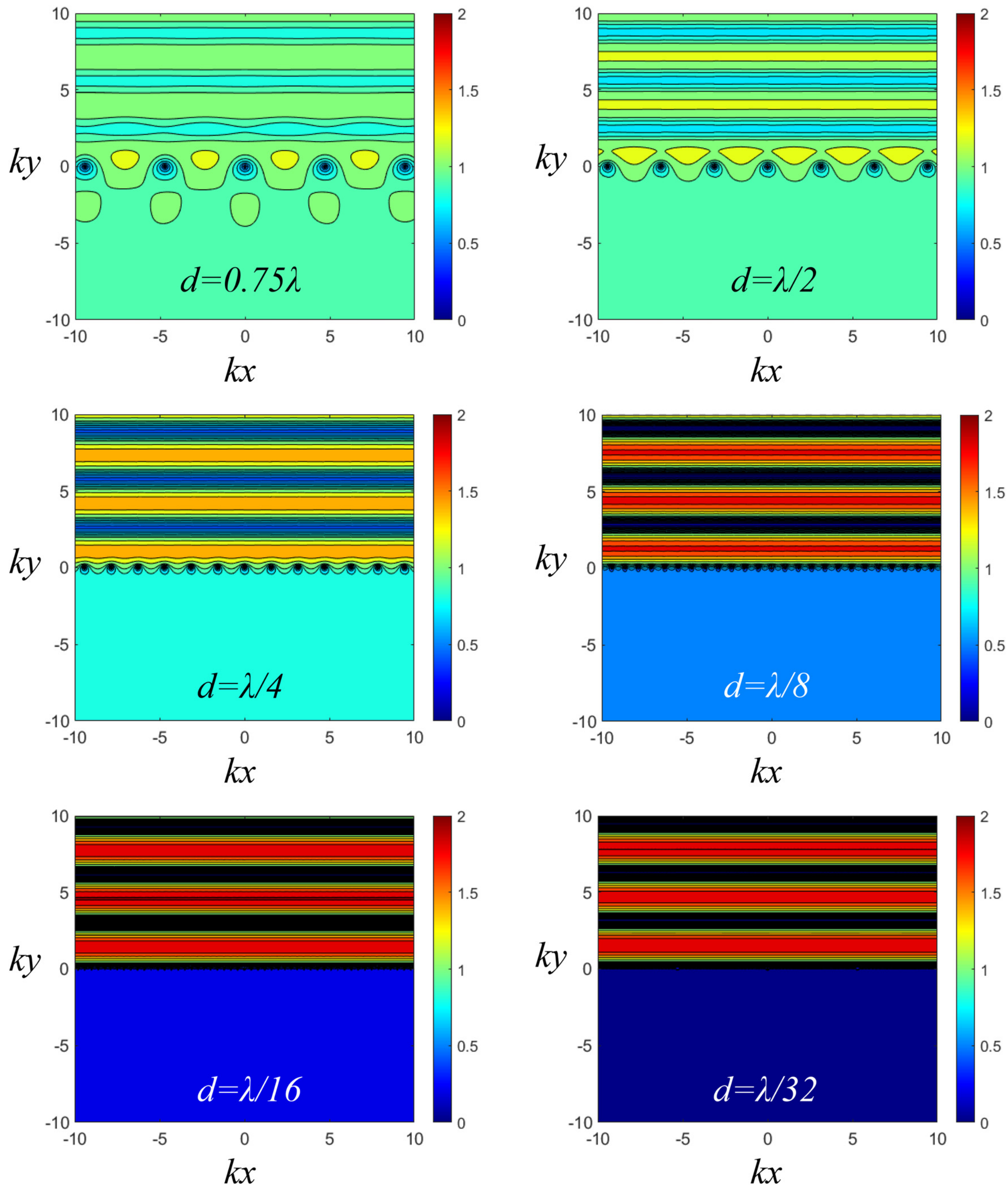


Fig. 5. (Color online) Loci of constant electric field amplitude levels $|\mathbf{E}|$, with $\mathbf{E}$ being the phasor of the sinusoidally time varying electric field. The perfectly conducting wires are located periodically at $y = 0$ with spacings shown on each diagram. For the last case, behind the shield the field is on the order of $-30\,\text{dB}$ (linear value $= 0.03$). The horizontal and vertical axes represent kx and ky, respectively. The radius a of the wires was chosen as $ka = 0.01$. Calculations are performed based on an implementation of formulas (14)–(16) in MATLAB (Ref. 13).

that in the limit for the frequency going to zero (14) leads to an exponential decay behind the screen, as also found by Feynman. The mathematical proof is beyond the scope of this paper.

C. Size of the shielded region for 2D shields

The canonical case considered is a plane wave hitting a perfectly conducting half plane, as in Fig. 6. The direction of incidence is normal to the half plane, and the polarization of the incident electric field is either parallel or normal to the edge of the half plane. This case is considered for two reasons. The main reason is that this geometry shows how an electromagnetic field "diffracts" at the edge, in this way reaching the region behind the shield. If properly applied, it allows an assessment of how close behind a shield, a device or component has to be located in order to reach a certain level of shielding. The second reason is the fact that this geometry is a classic one, already solved quasi-analytically by Sommerfeld in 1964 and very clearly described by van Bladel.[15,16] Because the mathematical derivation can be found in these references, the resulting expressions for the total field are provided without proof. For an incident electric field parallel to the edge, this field is

04 August 2024 09:01:49

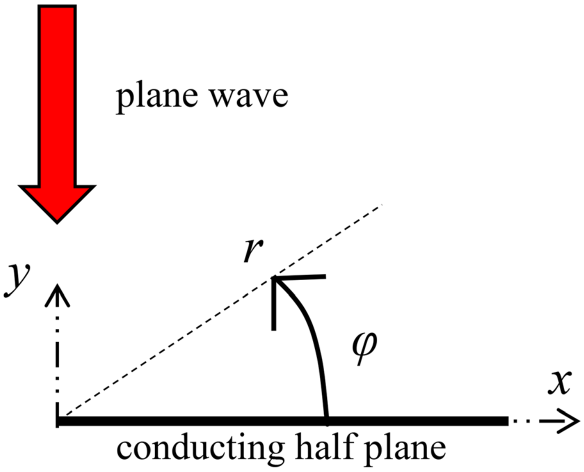


Fig. 6. (Color online) Plane wave hitting a conducting half plane.

$$E_z^{total} = j\sin(kr\sin\varphi) + \frac{1+j}{2} e^{jkr\sin\varphi} F\left(\sqrt{\frac{2kr}{\pi}}\left(\cos\left(\frac{\varphi}{2}\right) + \sin\left(\frac{\varphi}{2}\right)\right)\right) - \frac{1+j}{2} e^{-jkr\sin\varphi} F\left(\sqrt{\frac{2kr}{\pi}}\left(\cos\left(\frac{\varphi}{2}\right) - \sin\left(\frac{\varphi}{2}\right)\right)\right), \tag{17}$$

$$F(t) = \int_0^t e^{-1/2j\pi\tau^2} d\tau. \tag{18}$$

Expression (18) defines the so-called Fresnel integral that is used in expression (17), very well known in the diffraction theory. The loci where the ratio of the amplitude of the total electric field (i.e., incident field + field generated by the currents induced on the shield) over the amplitude of the incident field (i.e., simply the plane wave amplitude) is constant are given in Fig. 7. Of course, on the screen, the total (tangential) field is zero. It is seen in Fig. 7 that the shielding is better than 40 dB (a reduction in the field by a factor of 100) only in a very small region behind the half plane. Close to the edge of the half plane, this region is considerably thinner than further away. A shielding of 20 dB (i.e., a reduction of the field by a factor 10) is reached in a considerable region behind the half plane.

Through this canonical case, two general shielding properties are illustrated. In a specific point behind a shielding screen, the level of shielding depends on the ratio between the absolute distance from the screen and the absolute distance from the closest edge of the screen. However, it also depends on the *electrical* distance to the closest edge of the screen, i.e., the distance expressed as a number of wavelengths. Keeping the absolute point behind the screen, the same shielding will be better at higher frequencies, because this corresponds with moving further to the right in Fig. 7. Based on Fig. 7, a good estimate of the level of shielding can be made in each specific case.

In Fig. 7 also note the formation of a standing wave pattern at the right above the half plane. Going to the left of the half plane, i.e., where there is no shielding, the field rapidly approaches the amplitude 1, i.e., the original plane wave is just passing at the left of the half plane.

From a physical perspective, the fact that the fields reach the zone at the back of the shield can also be explained by using Huygens' principle: Each point within a "primary" wave front can be interpreted as a new source of a "secondary" spherical wave. The superposition of all these secondary spherical waves completely determines the shape of the forward propagating original wave at any subsequent time. So in this case, the secondary spherical waves emanating from the left half of the plane, i.e., where no shield is present, do reach the zone at the back of the shield. The amplitudes there are governed by the interference between all these secondary waves. Note that the field levels that are generated by this effect in practice are quite comparable to the levels observed when the shield is gridded or woven, of course depending on the size of the openings expressed in wavelength.

For a half plane with finite conductivity σ, a contribution to the total field behind the screen generated by the wave penetrating the shield has to be added. However, in Sec. IV D, it will be shown that this contribution in typical

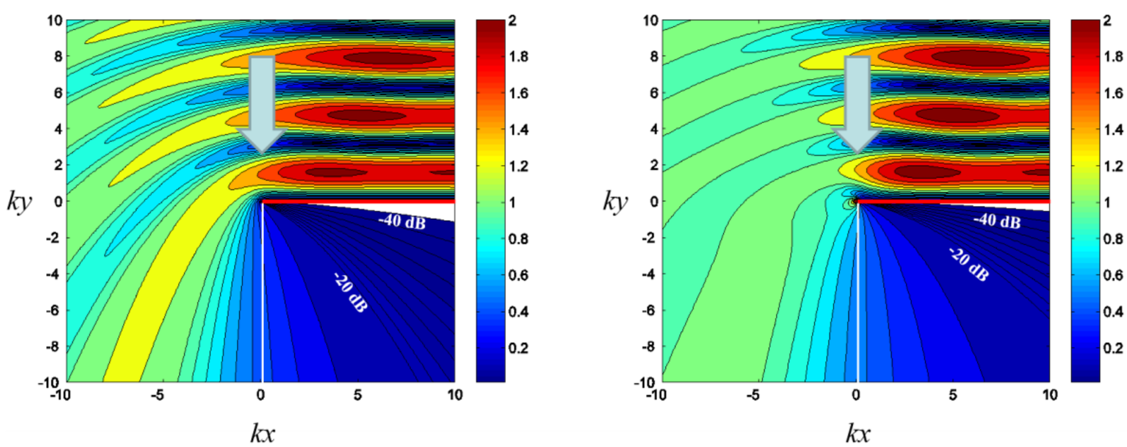


Fig. 7. (Color online) Loci of constant electric field amplitude levels $|\mathbf{E}|$, with $\mathbf{E}$ being the phasor of the sinusoidally time varying electric field. The perfectly conducting halfplane is depicted as a red line. The direction of the incident plane wave with amplitude 1 is marked in blue-grey. The horizontal and vertical axes represent kx and ky, respectively. The levels -40 dB (linear value = 0.01) and -20 dB (linear value = 0.1) are indicated. Both the incident electric field polarization parallel to the edge (left) and normal to the edge (right) are considered. The white zone in the figures is the zone with shielding better than 40 dB. Calculations are performed based on an implementation of formulas (17) and (18) in MATLAB (Ref. 13).

04 August 2024 09:01:49

shielding situations is on the order of -100 dB, which means that it is negligible in comparison with the contribution from the wave "going around the screen," as described in this section.

D. Penetration through a 2D shield with finite conductivity

This phenomenon is the only one that can be well-described by the classic textbook case of a plane wave hitting an infinite conducting screen. Most of the wave reflects. A small part of the wave enters the screen, where it decays in an exponential way while propagating further. This decay is governed by the skin depth of the metal of the screen. At the other end of the screen, a second reflection occurs and part of the wave leaves the screen again. This means that inside the screen, a situation with multiple reflections at the interfaces at both sides of the screen may occur. The rigorous analysis of this canonical case can be found in many textbooks and will not be repeated here. The final result for the transmission T of a normally incident plane wave can easily be expressed in closed form,[3,4]

$$T = \frac{1}{\mathrm{SE}\,(\text{linear})} = \left| \frac{4\eta_0\eta_s e^{-\gamma_s d}}{(\eta_s+\eta_0)^2-(\eta_s-\eta_0)^2 e^{-2\gamma_s d}} \right|, \tag{19}$$

$$\begin{aligned}\gamma_i &= \sqrt{j\omega\mu_i(j\omega\varepsilon_i+\sigma_i)}\\ &= \text{propagation constant in medium } i,\end{aligned} \tag{20}$$

$$\eta_i = \frac{j\omega\mu_i}{\gamma_i} = \text{characteristic impedance of medium } i, \tag{21}$$

where the subscript $i = 0$ represents the background medium and the subscript $i = \mathrm{s}$ represents the screen medium, which is a conductor. A widespread misconception is the belief that a good shield needs to have a thickness much larger than the skin depth at the frequency considered. Working out expression (19) for skin depths going to infinity (or frequencies going to zero) yields $T \simeq 2/(\eta_0\sigma_s d)$. If the background medium is air, then this further reduces to $T = 2/(Z_0\sigma_s d)$ where $Z_0 = 377\ \Omega$ is the impedance of free space. For a copper plate of thickness 0.1 mm, this gives a shielding level of ca. 120 dB. This means that if one considers only this contribution to the field behind the screen, this field is reduced by a factor of 10^6.

In other words, in most practical circumstances, with finite screens (see Sec. IV C), or with woven screens or mesh based screens (see Sec. IV B), the level of shielding is not determined by the penetration through the metal itself, but mainly by the presence of any (even small!) holes in the screen (as qualitatively described in Sec. IV B), or by diffraction at the edges of the screen (as qualitatively described in Sec. IV C).

From a practical shielding point of view, a detailed study of a plane wave hitting an infinite conducting screen in most cases is, thus, actually irrelevant. The exception is the so-called full-metal Faraday cage, i.e., a closed Faraday cage made of 2D shielding material without holes/openings, where the penetration through the metal fully determines the level of shielding.

V. MAGNETIC SHIELDING

The basic working mechanism of magnetic shielding is different. The reason is that there is no magnetic equivalent for the electric conductor; that is, a material with infinite magnetic conductivity that will respond in a way that the B-field inside is zero. The shielding of magnetic fields is a secondary effect, related to the shielding of the electric fields in the field configuration. It is qualitatively easily seen from the differential form of Faraday's law, i.e. (3), that in a region where the electric field is zero (or very small), the magnetic field will also be zero (or very small), provided that the frequency is not zero (or large enough).

We can study this in a more systematic way. It follows from (3) that inside a shield made of perfect electric conductor (thus, with conductivity $\sigma \to \infty$) for any frequency different from zero, the zero electric field automatically leads to a zero magnetic field. This is well known. The second step involves relating the zero field inside with the field just outside, just as in the case of the electric field. Applying (3) again, but now just above the surface of the shield, and taking into account that the tangential electric fields there are zero, we immediately see that just outside the shield the magnetic field component normal to the shield is zero. It is very important to emphasize that a shield (that essentially consists of electric conductors) does not shield the magnetic field components tangential to the shield in its immediate neighborhood. It just shields the normal component of this magnetic field. This means that there is a sudden jump of the tangential magnetic field at the surface of the shield from zero (or a very small value) inside to a considerable value just outside. For sufficiently high frequencies, the study of the "shielded zone" is very similar to the case of electric shielding and delivers results that are very similar. It is important to note that an identical result is obtained by building a line of reasoning fully based on eddy currents, as is traditionally done.

However, for sufficiently low frequencies, the situation is totally different. This is revealed by studying the relation among finite conductivity, the frequency, and magnetic shielding. A very educational way to do this is by studying the simple example of the magnetic field inside a loop of conducting wire, as in Fig. 8.

Applying the integral form of Faraday's law, Eq. (1), along the loop yields

$$RI = -j\omega\phi^{tot} = -j\omega(LI + \phi^{inc}), \tag{22}$$

where ϕ^{inc} is the incident magnetic flux going through the loop, which is directly related to the magnetic field normal to

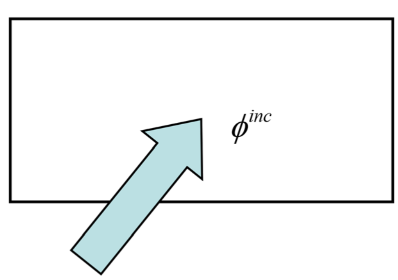


Fig. 8. (Color online) Loop with resistance R (due to the finite conductivity of the wire) and inductance L (due to the inductive self-coupling) in the presence of a time-varying applied magnetic flux ϕ_{inc} (Ref. 17).

04 August 2024 09:01:49

the loop area, and I is the current flowing in the loop. This can be solved as

$$I = \frac{-j\omega\phi^{inc}}{R + j\omega L}, \tag{23}$$

$$\phi^{tot} = \phi^{inc} + LI = \frac{1}{(1 + j\omega L/R)}\phi^{inc}. \tag{24}$$

The incident flux, which is the integral over the loop area of the magnetic field normal to the loop, is, thus, reduced by a factor that depends on $(\omega L/R)$. Any device positioned inside, or just in front or behind this loop, will experience this reduction of magnetic field and is, thus, shielded from this magnetic field component. For a perfect conductor, R equals zero, and the magnetic shielding is perfect. The incident flux is completely compensated. However, for any nonzero R, there exists a critical frequency $(R/L)/(2\pi)$ below which the shielding deteriorates to reach zero shielding at DC, i.e., for $\omega = 0$. This is a major difference with electric shielding.

This can be numerically illustrated by using the formulas for R and L for a copper loop of diameter D and wire radius a. These formulas can also be found in any basic textbook

$$R = \frac{\pi D}{\sigma \pi a^2} = \frac{D}{\sigma a^2}, \tag{25}$$

$$L = \mu_0 \frac{D}{2}\left(\ln\left(\frac{4D}{a}\right) - 2\right), \tag{26}$$

yielding

$$\omega_{crit} = \frac{R}{L} = \frac{\dfrac{D}{\sigma a^2}}{\mu_0 \dfrac{D}{2}\left(\ln\left(\dfrac{4D}{a}\right) - 2\right)} = \frac{2}{\mu_0 \sigma a^2\left(\ln\left(\dfrac{4D}{a}\right) - 2\right)}. \tag{27}$$

For $D = 1$ m and $a = 1$ mm, this delivers a critical frequency of $f_c \approx 694$ Hz. At 60 Hz, this yields a reduction of the amplitude of the incident flux by a factor 1.0037, which is negligible.

Note that a full shield can always be seen as a superposition of an infinite number of loops, each with its own current. The effect is the same. For real-life conductors with finite conductivity, magnetic shielding does not work for sufficiently low frequencies. This result is impossible to obtain from the "plane wave understanding" of shielding.

The practical consequences are severe. Whereas from a technical point of view, it is easy to shield houses from the radiation generated within the context of wireless communication networks, it is almost impossible to shield houses from the magnetic fields generated by the high-voltage power distribution lines. The reason is that the frequency there is only 50 or 60 Hz. These two forms of "radiation" are highly controversial in the present day society, where a considerable portion of the people is concerned with the radiation exposure issue.

Note that it is possible to implement magnetic shielding based on another operational principle. Shields can be made with high-permeability alloys like mu-metal. This type of shield works not by blocking or reflecting magnetic fields but by providing a preferred path for the magnetic field lines around a shielded area, a consequence of the high permeability. This means that the best shape for this type of magnetic shields is a closed container surrounding the shielded space. The electric analog is a container made of high permittivity materials, which essentially does the same thing for the electric field. In the engineering community, this technique is traditionally not thought of as a real "shielding" technique, and it is very rarely used in practice. However, from a physics point of view, it is related. A high conductivity or a high permittivity then just means working with the imaginary part or the real part of the complex permittivity. Both result in shielding properties. A more detailed discussion on this is beyond the scope of this paper.

VI. CONCLUSION

In this paper, the basics of electromagnetic shielding have been reviewed. This is done from a physical point of view, explaining the nature of the phenomena on the basis of rigorous mathematical formulations for very simple canonical cases. The issue was considered from the perspective of how an incident wave can reach the zone at the back of a shield: through the metal of the shield, through holes in the shield, or via the edges of the shield. For most practical shields, the first route leads to negligible fields. The second and third routes are the ones that need to be considered in real practical cases. Depending on the situation and frequency considered, for appropriate shields they typically give reductions of the field levels in the order of a few tens of dB.

The questions asked in the introduction can now be answered.

- There is indeed a difference in the behavior of a screen at low and high frequencies. At low frequencies, electric shielding can be largely maintained, whereas magnetic shielding properties largely get lost. At high frequencies, however, electric and magnetic shielding become very similar.
- Shielding does not only work for two-dimensional screens but also for wire grids and, to a certain extent, even for single wires. The main difference is the level of shielding and the region in space where the shielding is occurring.
- The traditional "educational" plane wave description of shielding is typically used at high frequencies, and it is valid for both types of shielding since they are inherently linked there. The description on the basis of eddy currents is typically used for magnetic shielding at lower frequencies. However, in principle, the eddy currents and the currents flowing in the screen of the plane wave description are essentially the same electric currents. In the plane wave description, they are somehow "invisible," since this description typically works with reflection and transmission coefficients without really considering the electric currents.

AUTHOR DECLARATIONS

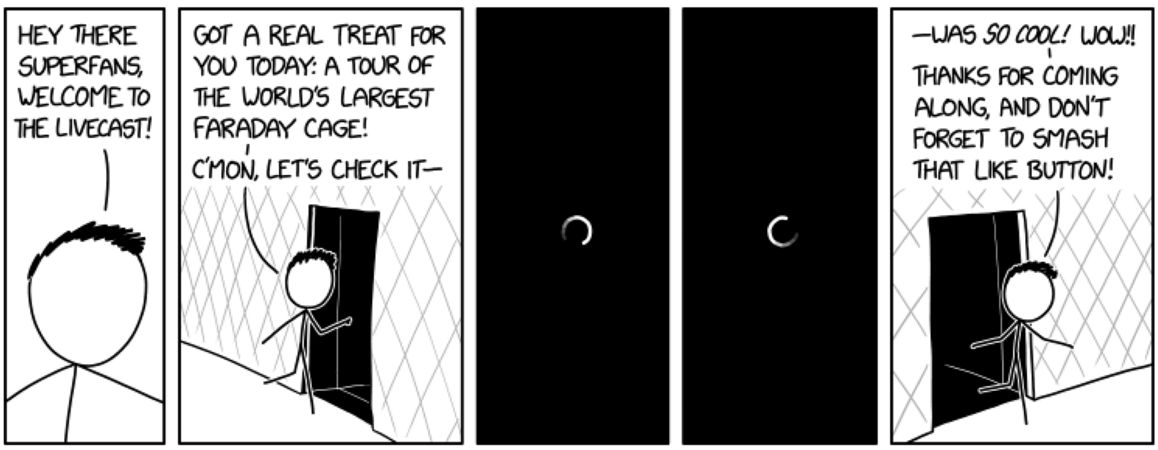
Conflict of Interest

The author has no conflicts of interest to declare. There is no financial interest to report. I certify that the submission is original work.

04 August 2024 09:01:49

[a]Electronic mail: guy.vandenbosch@kuleuven.be, ORCID: 0000-0002-5878-3285.

[1]See <www.lessemf.com> for information on many practical forms of shielding, here related to the controversy about electromagnetic fields in our society.
[2]H. Ott, *Electromagnetic Compatibility Engineering* (John Wiley & Sons, New York, 2009).
[3]S. Celozzi, R. Araneo, and G. Lovat, *Electromagnetic Shielding* (John Wiley & Sons, New York, 2008).
[4]K. L. Kaiser, *Electromagnetic Shielding* (CRC, Taylor & Francis Group, Boca Raton, FL, 2006).
[5]S. Fahy, C. Kittel, and S. G. Louie, "Electromagnetic screening by metals," Am. J. Phys. **56**, 989–992 (1988).
[6]W. M. Saslow, "Maxwell's theory of eddy currents in thin conducting sheets, and applications to electromagnetic shielding and MAGLEV," Am. J. Phys. **60**(8), 693–711 (1992).
[7]L. Kowalski, "About electrostatic shielding," Phys. Teach. **27**, 366–367 (1989).
[8]P. Rochon and N. Gauthier, "Strong shielding due to an electromagnetically thin metal sheet," Am. J. Phys. **58**, 276–277 (1990).
[9]Z. Geller and E. Bagno, "Does electrostatic shielding work both ways?," Phys. Teach. **32**(1), 20–22 (1994).
[10]R. B. Schulz, V. C. Plantz, and D. R. Brush, "Shielding theory and practice," IEEE Trans. Electromagn. Compat. **30**(3), 187–201 (1988).
[11]K. F. Casey, "Electromagnetic shielding behavior of wire-mesh screens," IEEE Trans. Electromagn. Compat. **30**(3), 298–306 (1988).
[12]J. M. Aguirregabiria, A. Hernandez, and M. Rivas, "Shielding of an oscillating electric field by a hollow conductor," Am. J. Phys. **64**(8), 1008–1013 (1996).
[13]See supplementary material at https://www.scitation.org/doi/suppl/10.1119/5.0087295 for "Matlab scripts."
[14]R. P. Feynman, R. B. Leighton, and M. Sands, *The Feynman Lectures on Physics II: Commemorative Issue, Three Volume Set* (Addison Wesley, Boston, 1989), Sec. 5–7.
[15]A. Sommerfeld, *Optics* (Academic, New York, 1964).
[16]J. Van Bladel, *Singular Electromagnetic Fields and Sources* (Oxford Science Publications, Clarendon, Oxford, 1991).
[17]G. A. E. Vandenbosch, "How to model connection wires in a circuit: From physical vector fields to circuit scalar quantities," Am. J. Phys. **81**(9), 676–681 (2013).



I asked them if it was safe to be running tours during the pandemic. They said, "During the what?" (Source: https://xkcd.com/2338/)

04 August 2024 09:01:49