Minimizing the reflection of electromagnetic waves

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Content

1.0 Introduction

The treatment of this subject requires knowledge the results of Maxwell's theory for the behavior of electromagnetic waves in vacuum and in media. Also important in this context is the theory of refraction and reflection of plane waves and the theory of conduction.

With these prerequisites, the problem of the topic can be traced back to trivial, formal consideration in electrical engineering.

Further, when considering the electromagnetic wave, I confine myself to the far field, so the wave decreases in proportion to the reciprocal of r when r is the distance from the origin.

2.0 Model

The minimization of the reflection of electromagnetic waves requires that any reflection takes place. Reflections of electromagnetic waves on highly conductive metal surfaces are particularly intense. As practical examples aircraft, ships and submarines are mentioned.

In addition to the geometry, the reflection is determined by the surface texture. This one comes to the following model:

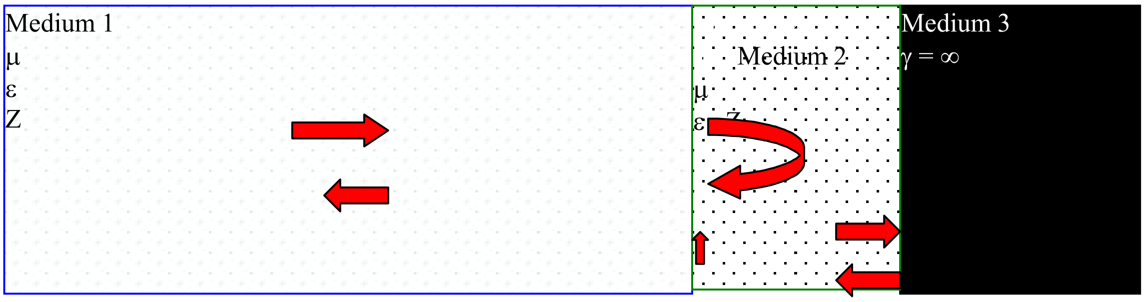


Figure 1

An electromagnetic wave propagates spherically from its origin and is described by the wave equation with free space damping, damping constant and phase constant [1], [2], [3]. Medium 1 can be attributed to the characteristic impedance Z1 due to its physical properties.

The wave penetrates through the interface in medium 2 and again propagates in the direction away from the origin by free space damping, damping constant and phase constant (now for medium 2). Because of the other physical properties of medium 2, another characteristic impedance Z2 results. Part of the wave penetrated in medium 2 is reflected. This reflection is described by the reflection factor p12. This reflection factor is defined by the characteristic impedances of medium 1 and medium 2 and 3.

If medium 3 is assumed to be electrically conducting, the part of the electromagnetic wave not reflected on the boundary layer 1-2 and attenuated on the further path through medium 2 is totally reflected at the boundary layer 2-3 and further attenuated on its return path through medium 2.

It is easy to see that in this model medium 1 is the propagation medium, medium 2 is a color protection layer and medium 3 is a constructive exterior wall.

In technical application, apart from special cases, medium 1 will be either free space, the atmosphere of the earth or seawater. Medium 2 is a dielectric insulating material and medium 3 is a metal. The total reflection taking place at the boundary layer 2-3 can hardly be changed, because the material condition of medium 3 is defined mechanically constructively.

Medium 1, the propagation medium of the electromagnetic wave, is determined by the environment. The consequence of this consideration is that a minimization of the reflection of electromagnetic waves can only take place at the border view 2-3 and in medium 2. Therefore, the propagation mechanism in media should now be described mathematically.

3.0 Electromagnetic waves in media

The electromagnetic wave is described by the wave equation (equation 1) with damping constant (equation 2) and phase constant (eq. 3) [1],[3]:

$$\mathbf{E}(x,t)=\mathbf{E_0}/4/\pi/r\ e^{-\alpha x}\ e^{j(\omega t\ -\ \beta x)} \qquad \text{(eq. 1)}$$

$$\alpha=\omega\mathrm{sqrt}\{1/2\mu\varepsilon[\mathrm{sqrt}(1+(\gamma/\omega/\varepsilon)\hat{}2)-1]\} \qquad \text{(eq. 2)}$$

$$\beta=\omega\mathrm{sqrt}\{1/2\mu\varepsilon[\mathrm{sqrt}(1+(\gamma/\omega/\varepsilon)\hat{}2)+1]\} \qquad \text{(eq. 3)}$$

Let's take a look at this and choose the medium seawater with a relative dielectric constant er = 81 and a specific electrical conductivity of $\gamma=10^{-6}\ m/\Omega/mm^2$.

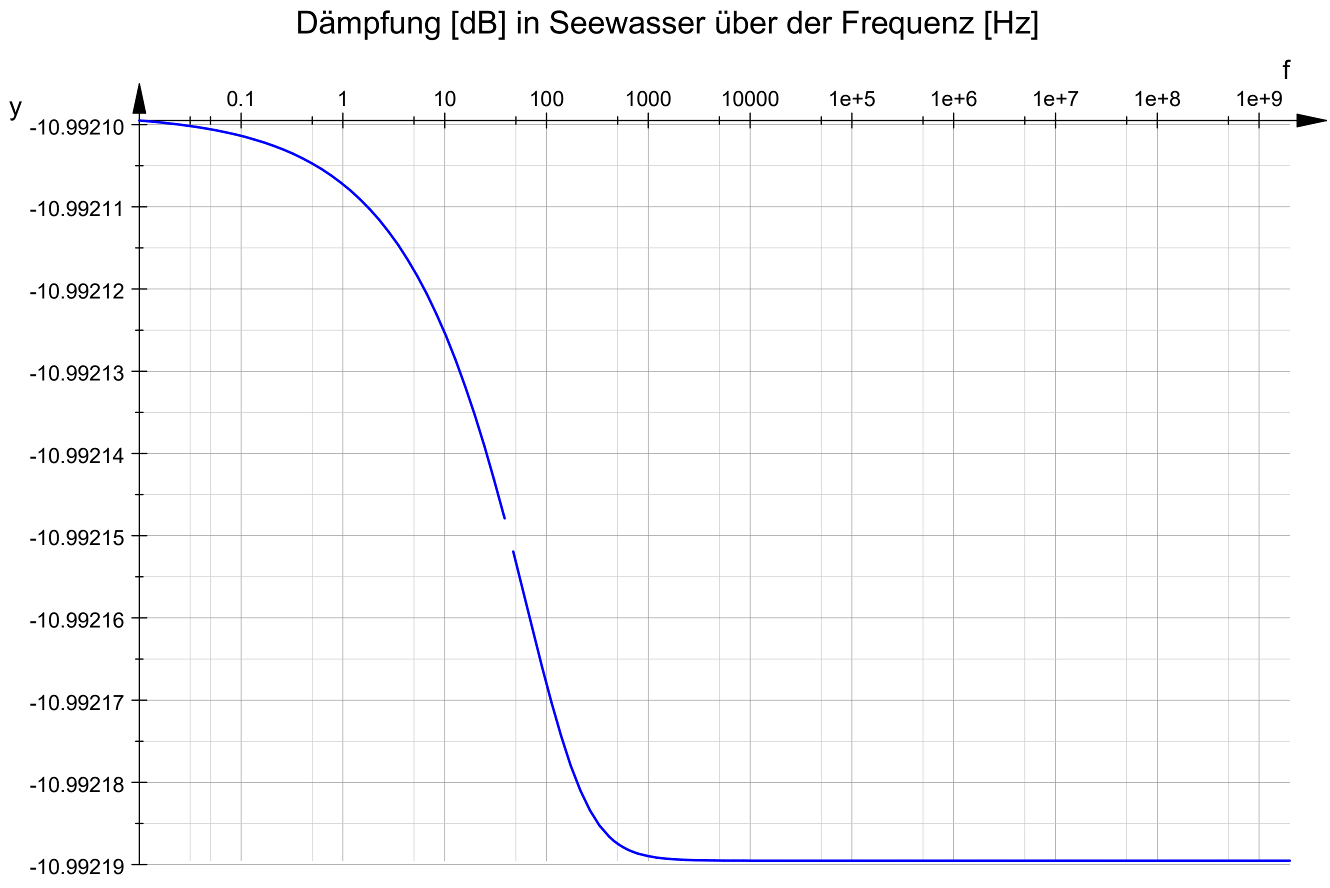


Figure 2 Amount of equation 1 in dB as function of frequency f

You can see three areas, which can be described as a line area, transition area and wave area. In the line area, electrical conduction takes place by means of charge carrier transport. The damping is caused by loss of the ohmic resistance of the seawater. As the frequency increases, the electrical conduction decreases and an electromagnetic wave occurs, the attenuation of which does not depend on the frequency

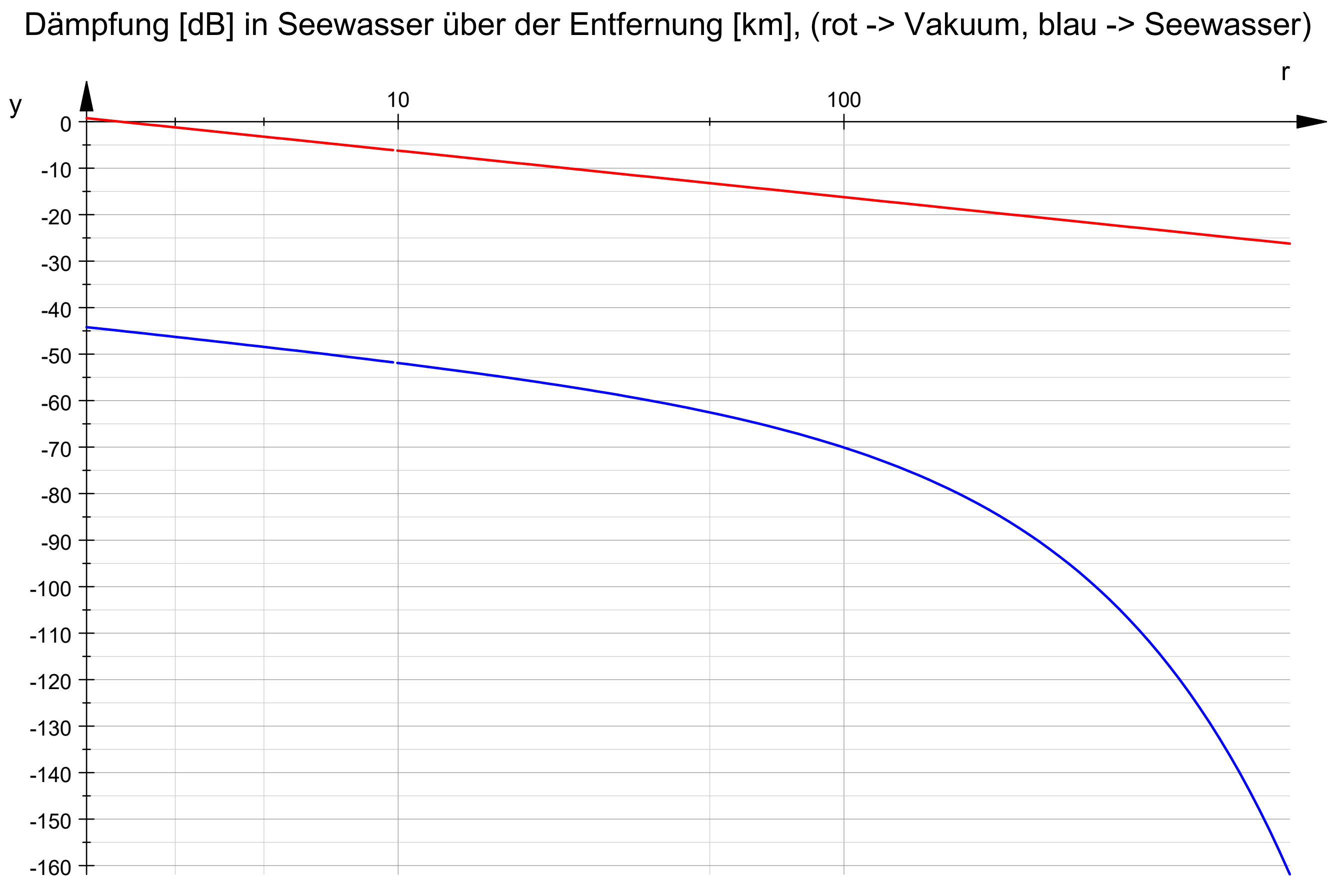


Figure 3 - Amount of equation 3 in dB as function of the distance r and the free space loss

Figure 3 shows the attenuation of electromagnetic waves in seawater over the distance. For comparison, the free space damping is drawn with. The different damping behavior at longer distances in seawater and in vacuum is clear.

For the sake of completeness, the phase characteristic and the phase velocity as a function of the frequency are also to be drawn.

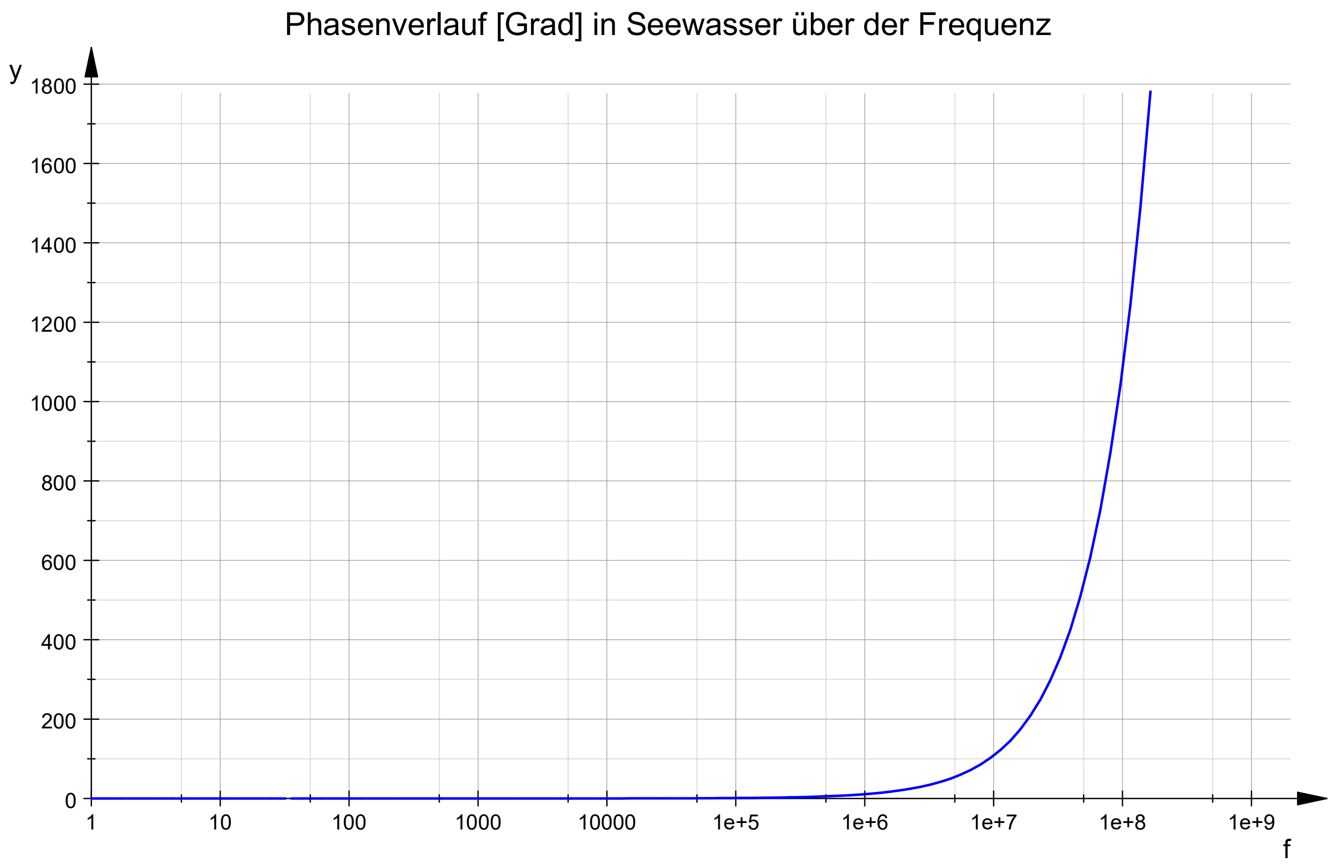


Figure 4 - Phase progression in Degrees in seawater over the frequency f

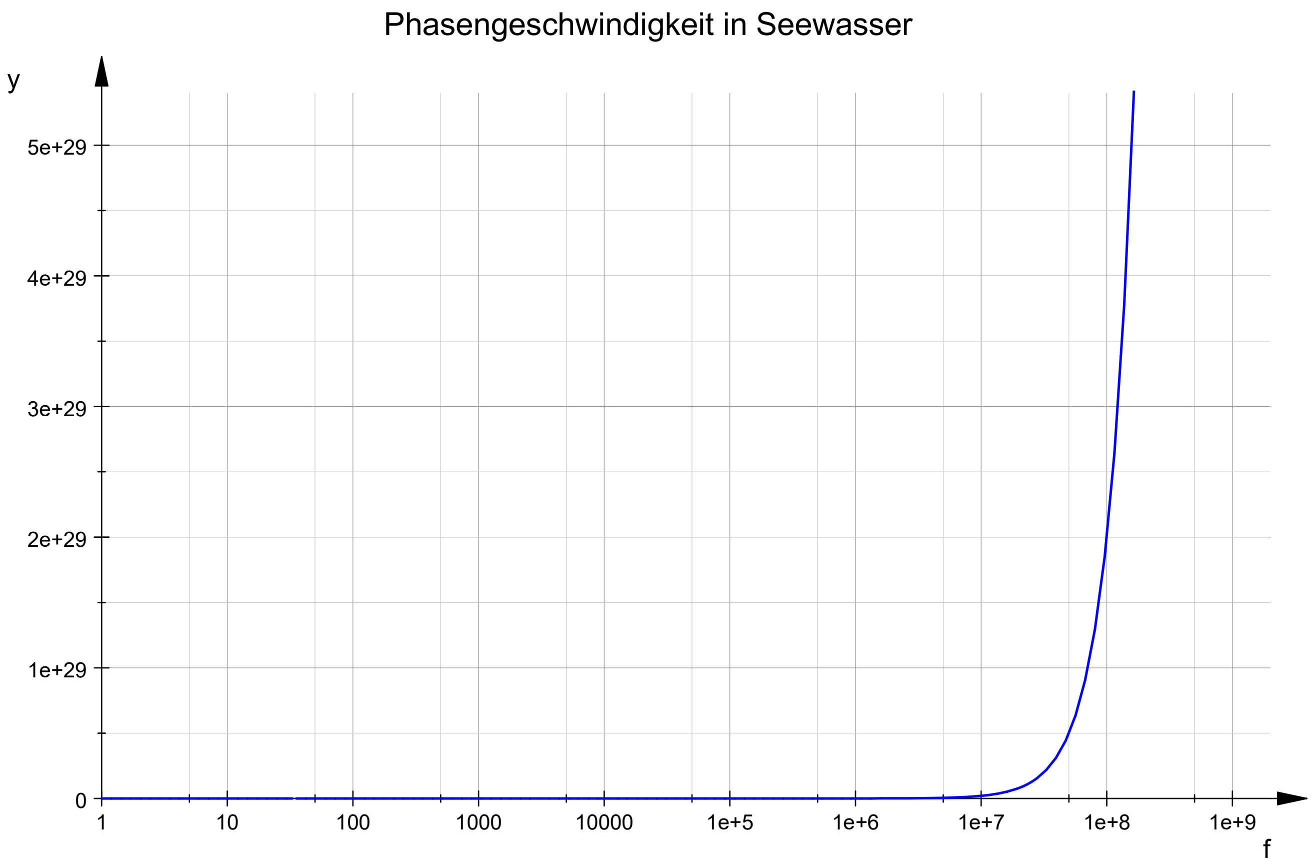


Figure 5 - Phase velocity when propagating in seawater over frequency f

This describes the electromagnetic wave in media using the example of seawater. Other media have different physical constants γ, μ, ε.

4.0 Reflection minimization

From the theory of electrical lines it is known that the reflected power at the end of the line is minimal and thus the power delivered to the load resistor becomes maximum when the condition

$$Z_{Last} = Z^{*}_{Leitungsende}$$

is satisfied. In this case, leading and returning power are about the same size and there is adjustment. This also applies [1] for electromagnetic waves in two media with the characteristic impedance Z1 and Z2.

$$Z_w=\mathrm{sqrt}(\mu/\varepsilon) \qquad \text{(eq. 4)}$$

It is therefore necessary to ensure that the characteristic impedance of medium 2 together with medium 3 in the model corresponds at least in absolute value to the real characteristic impedance of the propagation medium 1. Then about half of the amount of the incoming electromagnetic wave is reflected. That is the physically achievable minimum. The phase change in the reflection is not of interest.

Medium 2 is now a dielectric insulator with loss resistance, ie a capacitor with the capacity

$$C=\varepsilon_0\varepsilon_r A/d \qquad \text{(eq. 5)}$$

where d is the thickness of the medium 2 and A is the area of 1 m^2, ie 10^6 mm^2 [1].

The loss resistor, which is technically parallel to the capacitor, has the resistance value

$$R=d/\gamma/A \qquad \text{(eq. 6)}$$

Where d is the thickness of the medium 2 and A is the area of 1 m^2 so 10^6 mm^2 [1]. γ is the specific electrical conductivity of the dielectric material. From the point of view of line theory, therefore, the characteristic impedance of medium 1 to the magnitude of the characteristic impedance of the medium 2 and medium 3 of

$$|Z_2| = \left| \frac{d\ 10^{-6}}{\gamma\ mm^2 + j\omega\varepsilon_0\varepsilon_r\ mm^2} \right|$$

adapted as much as possible.

This equation can be solved for γ, bearing in mind that γ has to become real and positive for physical reasons.

$$\gamma=\mathrm{sqrt}(\,|(d*10^{-6}/Z_1/mm^2)^2 - (2\pi f_C\varepsilon_0\varepsilon_r)^2|\,) \qquad \text{(eq. 7)}.$$

Z_{Last} can also be broken and γ determined from the poles. Then, with Equation 5 and Equation 6 in

$$Z_2 = \frac{1}{1/R' + j\omega C'}$$

$$Z2 = \frac{d/A}{\gamma[1+(\omega\varepsilon_0\varepsilon_r/\gamma)^2]} - j\omega \frac{\varepsilon_0\varepsilon_r d/A}{\gamma^2 + (\omega\varepsilon_0\varepsilon_r)^2} \qquad \text{(eq. 7a)}$$

$$\gamma = 2\pi f_C \varepsilon_0 \varepsilon_r \qquad \text{(eq. 7b)}$$

Where f_C is the cut-off frequency. At larger frequencies, the reflection properties at the transition to medium 2 improve again.

Thus, the required specific electrical conductivity of the material in medium 2 can be calculated. His unity results in $m/(\Omega mm^2)$. Medium 2 is now physically adaptable.

$\varepsilon_0\varepsilon_r$ incidentally, it is proportional to the cosine of the angle of the flowing current to the surface normal vector on medium 2 in space. This angle becomes 90° at f_c. The current thus flows over the surface of the resulting by the skin effect capacitor C 'at the interface between medium 1 and 2.

In turn, one can conclude that the skin effect is not an electromagnetic wave, as some scientists claim, but is based on a pure displacement process of charge carriers, with ohmic sequence.

5.0 Example

d=500 µm, f= 1.5 GHz, Medium 1: ε_r=1, Medium 2: ε_r=8

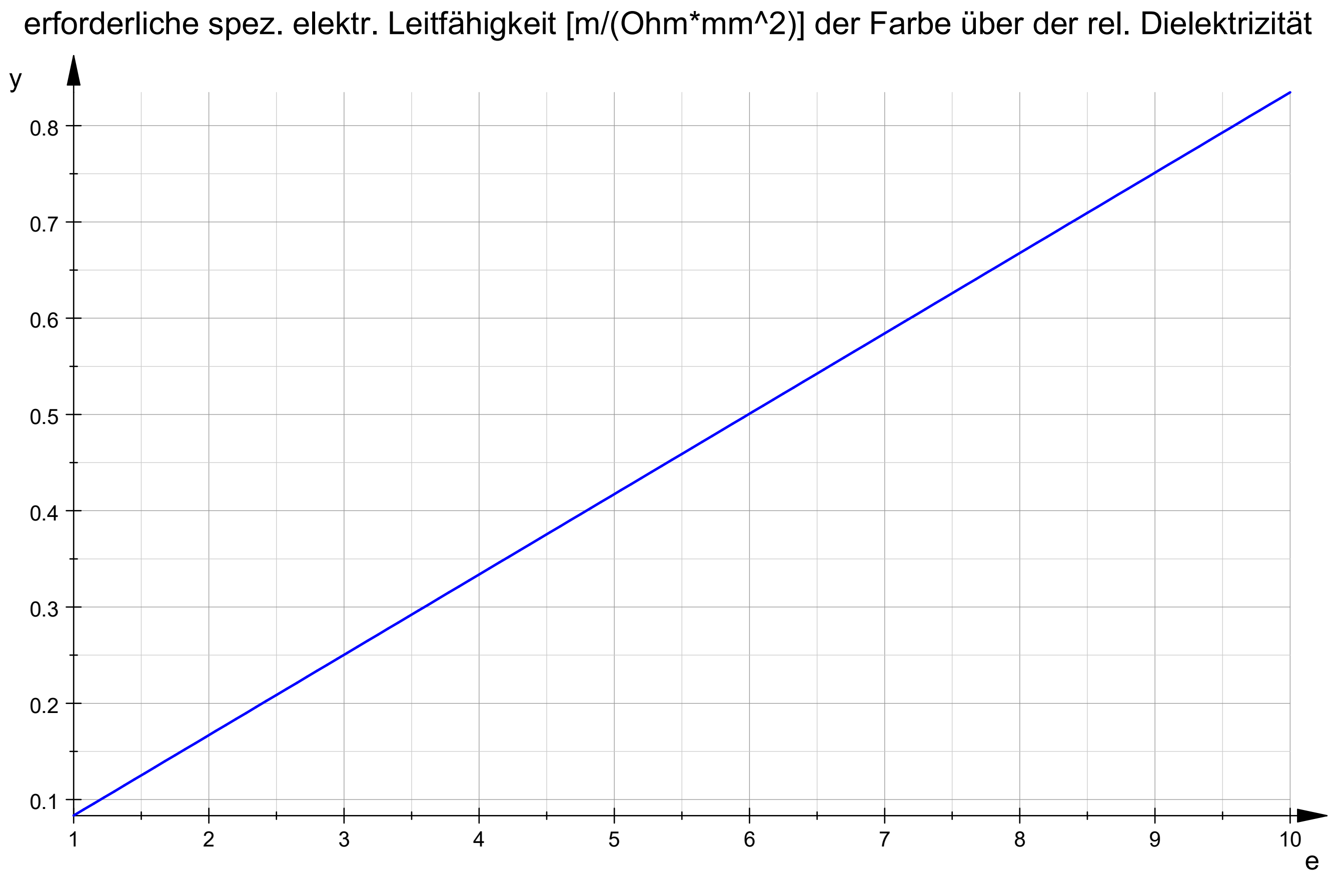


Figure 6 - calculated required specific electrical conductivity for medium 2

The calculated specific electrical conductivity is

$$\gamma = 0.6677.$$

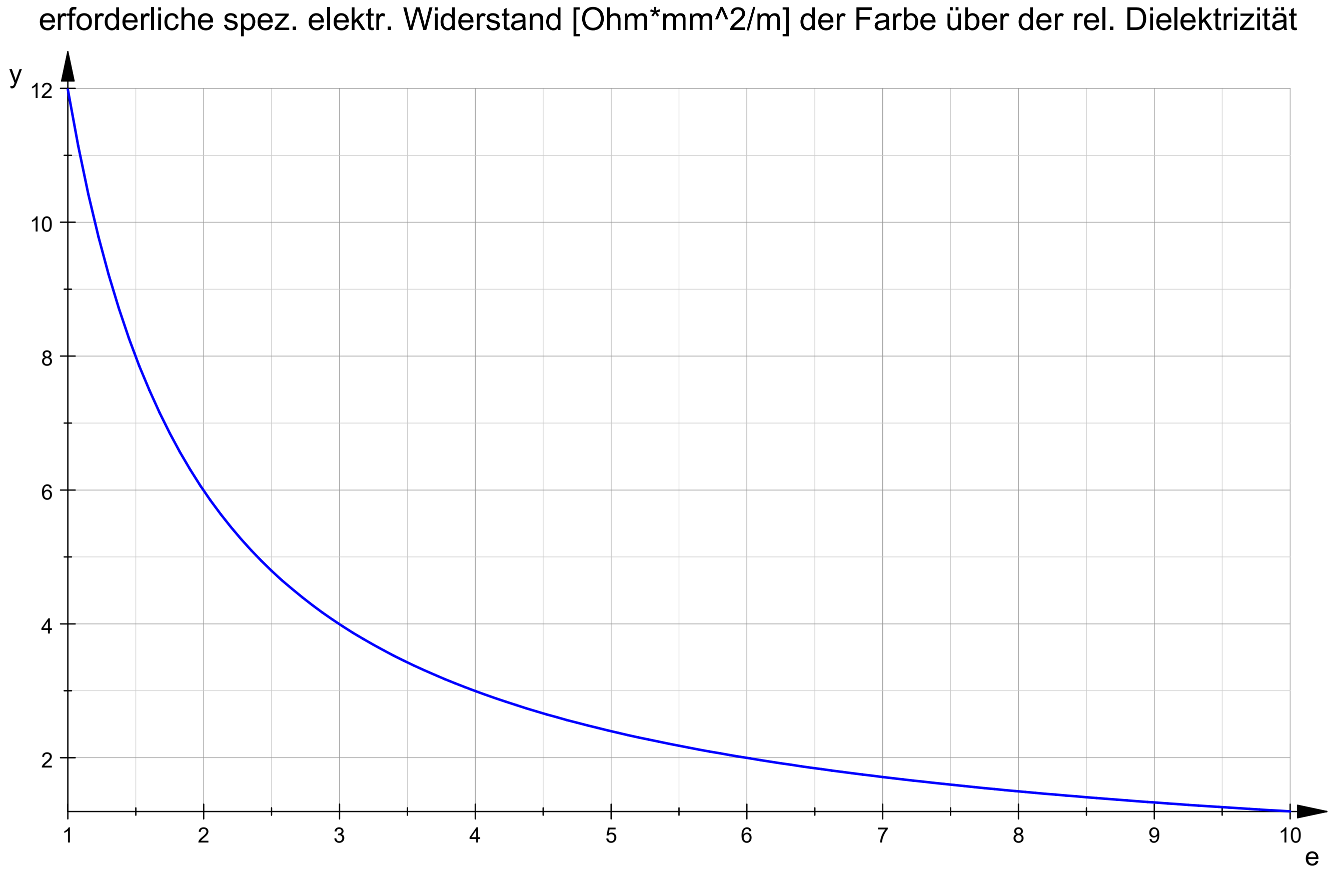


Figure 7 - the specific resistance resulting from figure 6

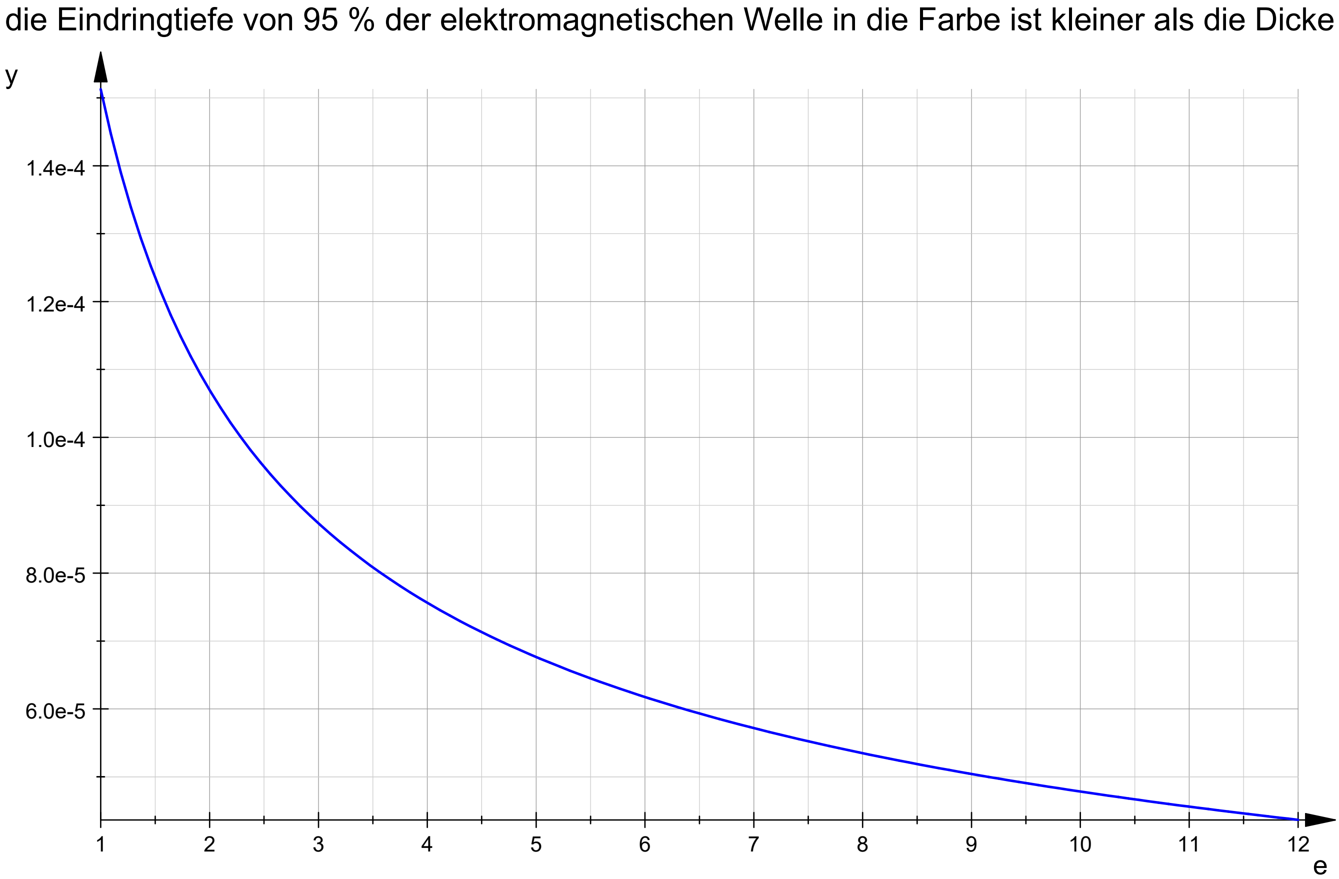


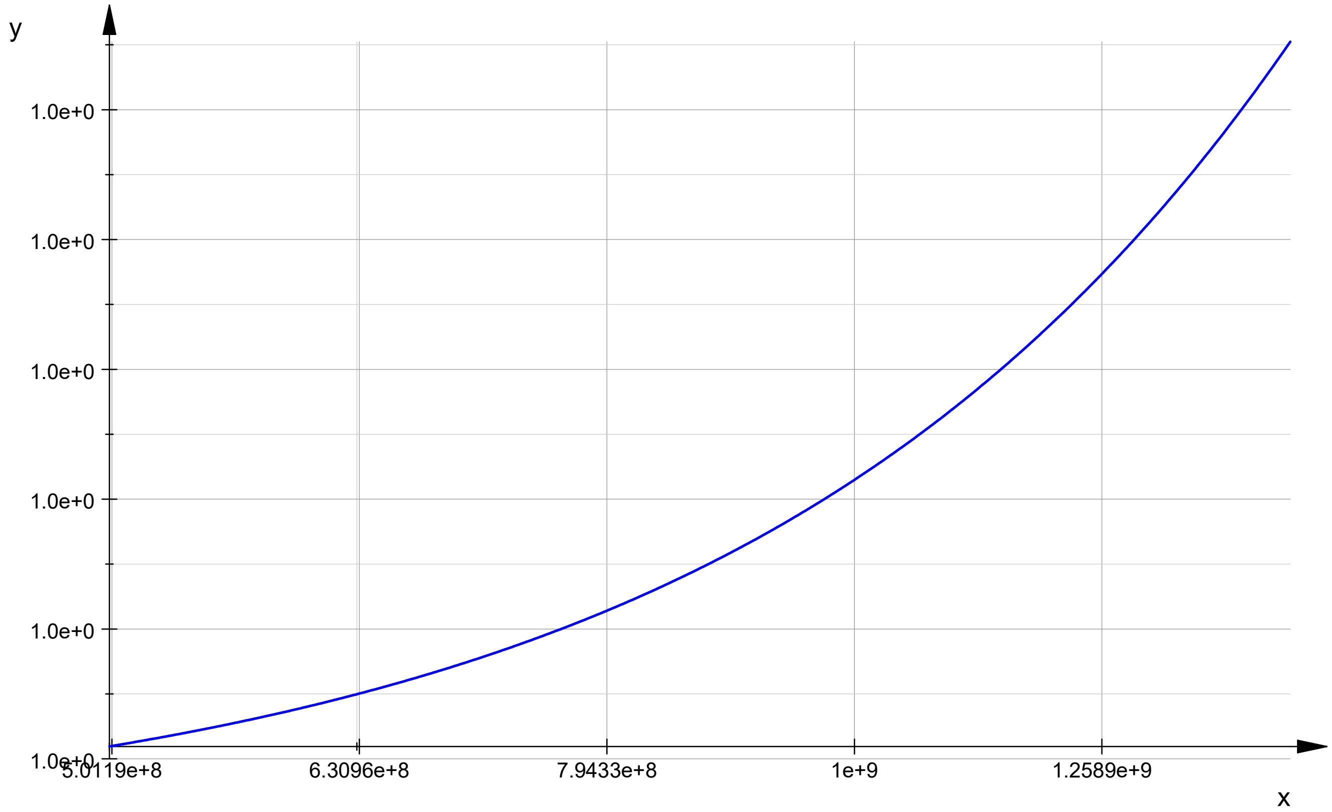
Figure 8 - 3 times the penetration depth of the electromagnetic wave in medium 2

The penetration depth of the electromagnetic wave in medium 2 was calculated with

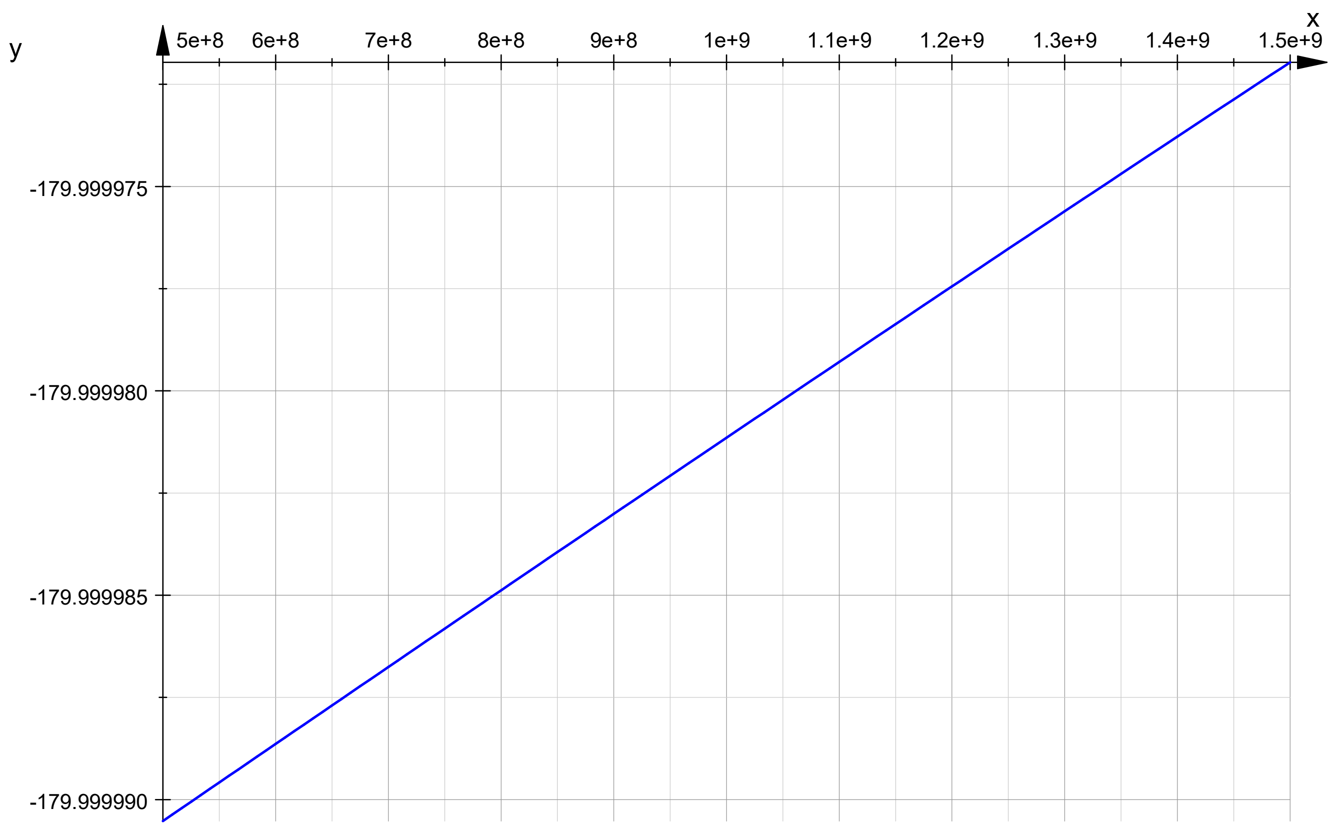
$$\delta = 3/\mathrm{sqrt}(\pi f \gamma \mu) \qquad \text{(eq. 8).}$$

The function graph specifies the values for a 95% damping of the shaft in medium 2. These values are much smaller than the thickness of the medium.

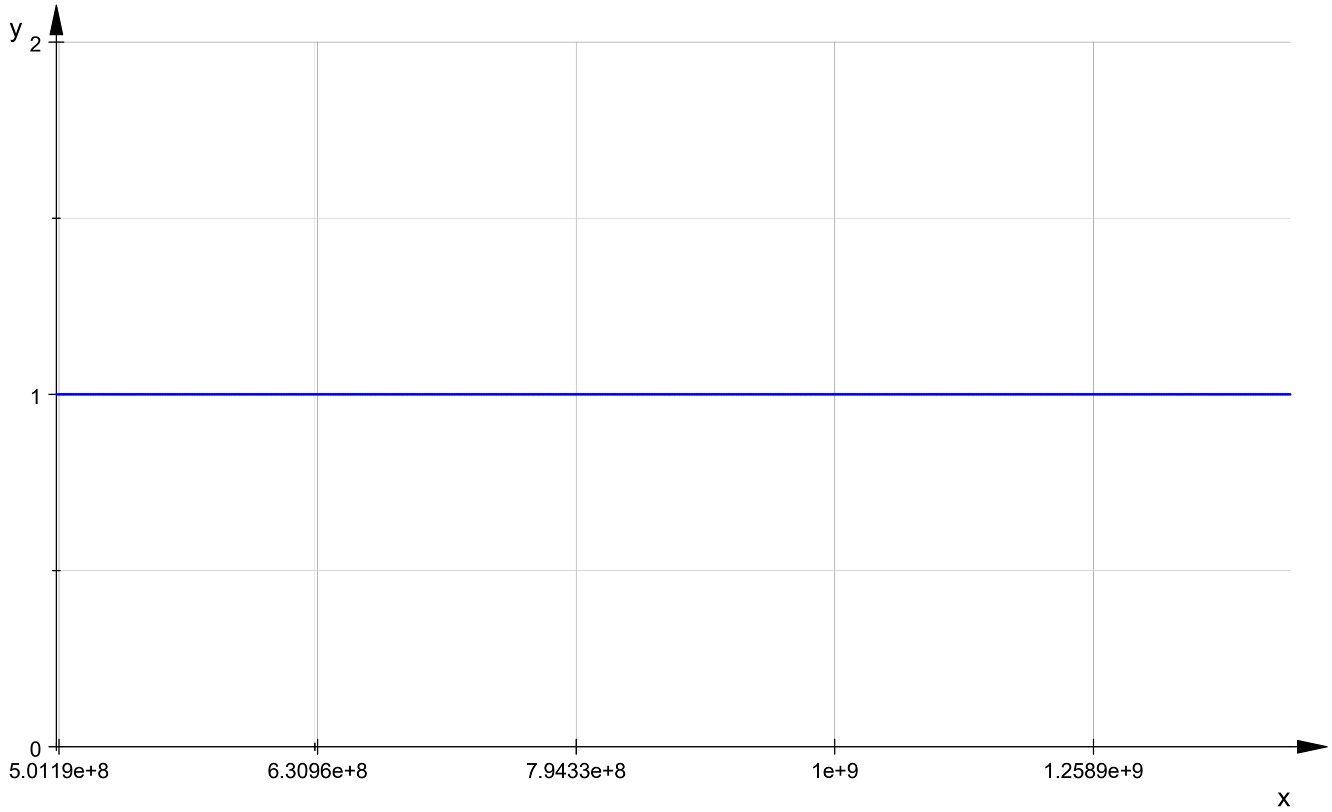
Betrag des sich ergebenden Reflexionsfaktors 1



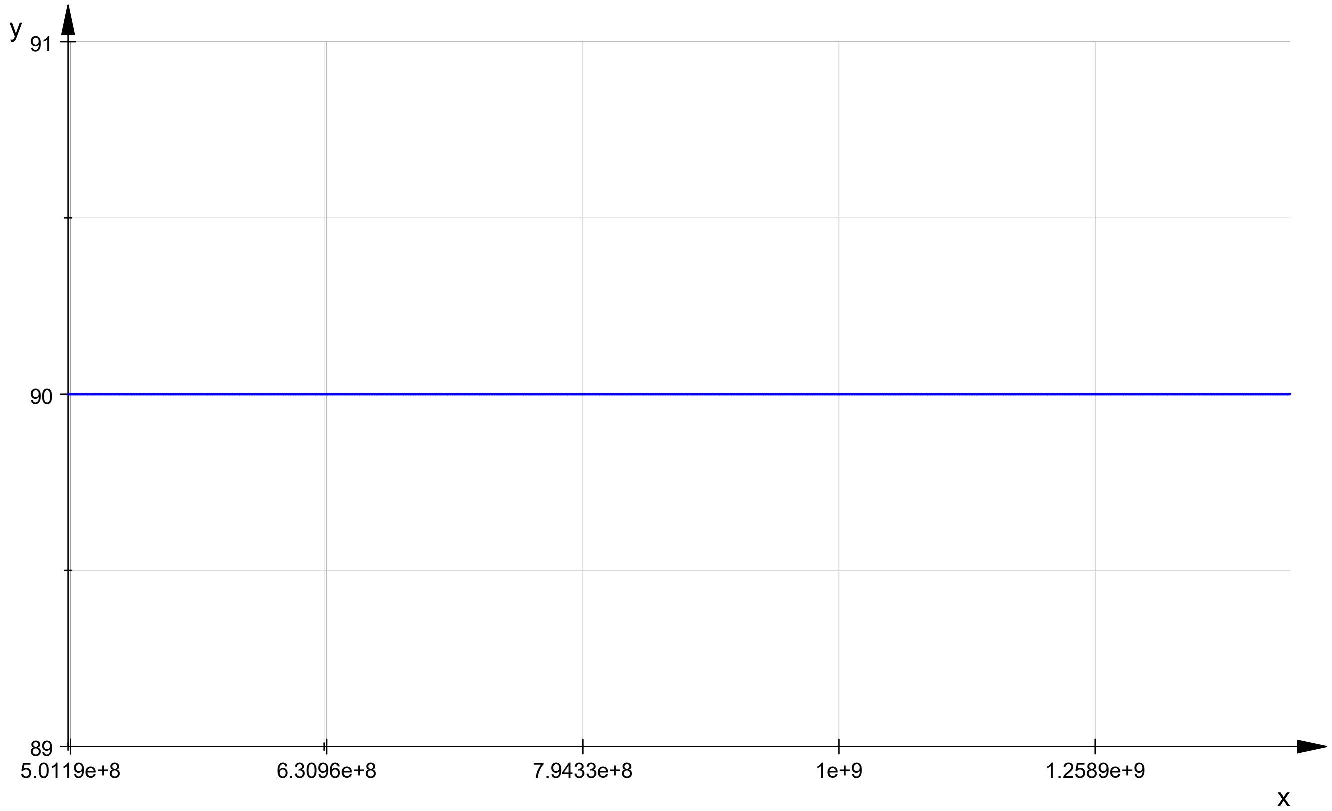
Winkel des sich ergebenden Reflexionsfaktors 1



Betrag des sich ergebenden Reflexionsfaktors 2



Winkel des sich ergebenden Reflexionsfaktors 2



The amount of the calculated electrical reflection factor 1 is

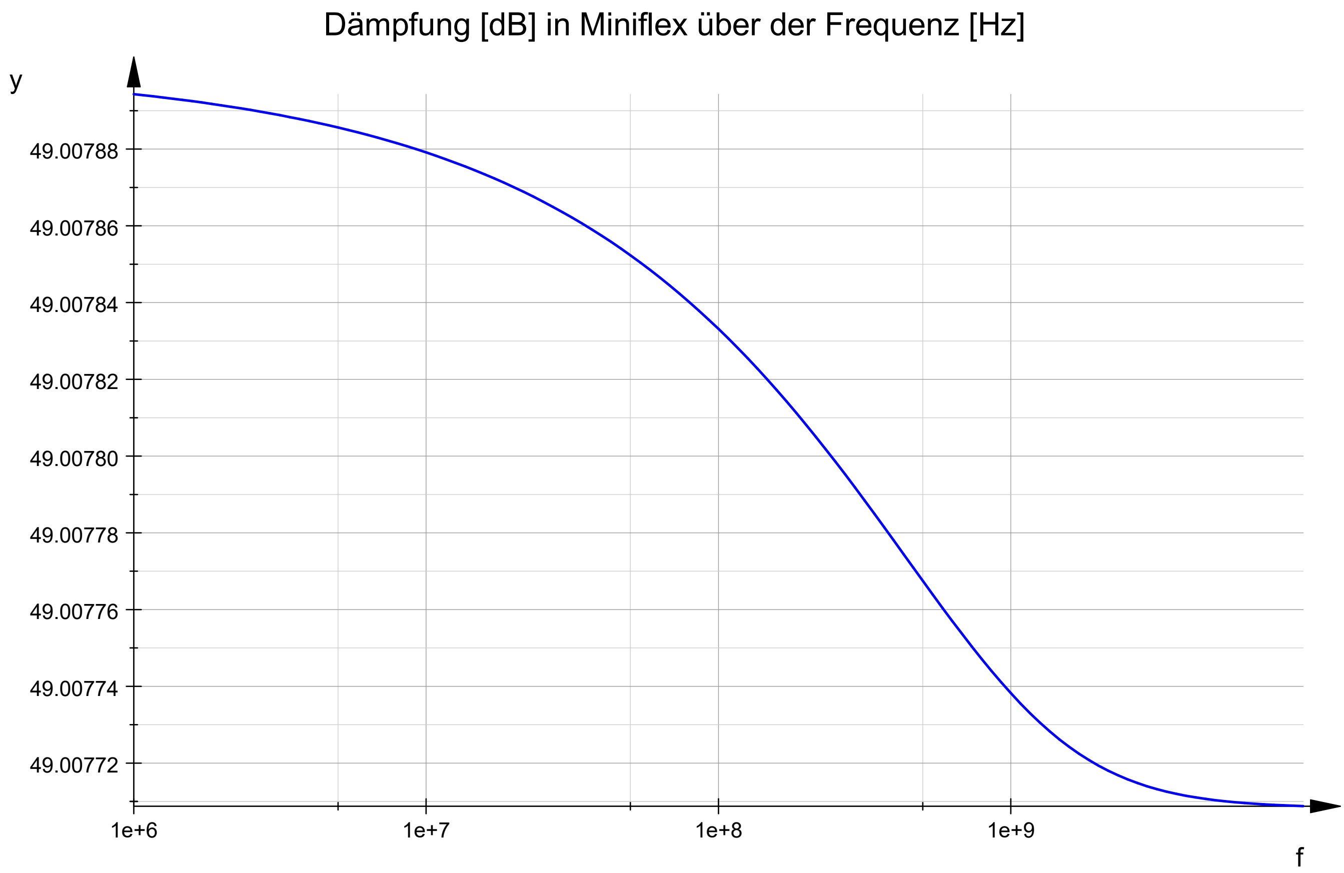
0.99999999999608522966987364765262

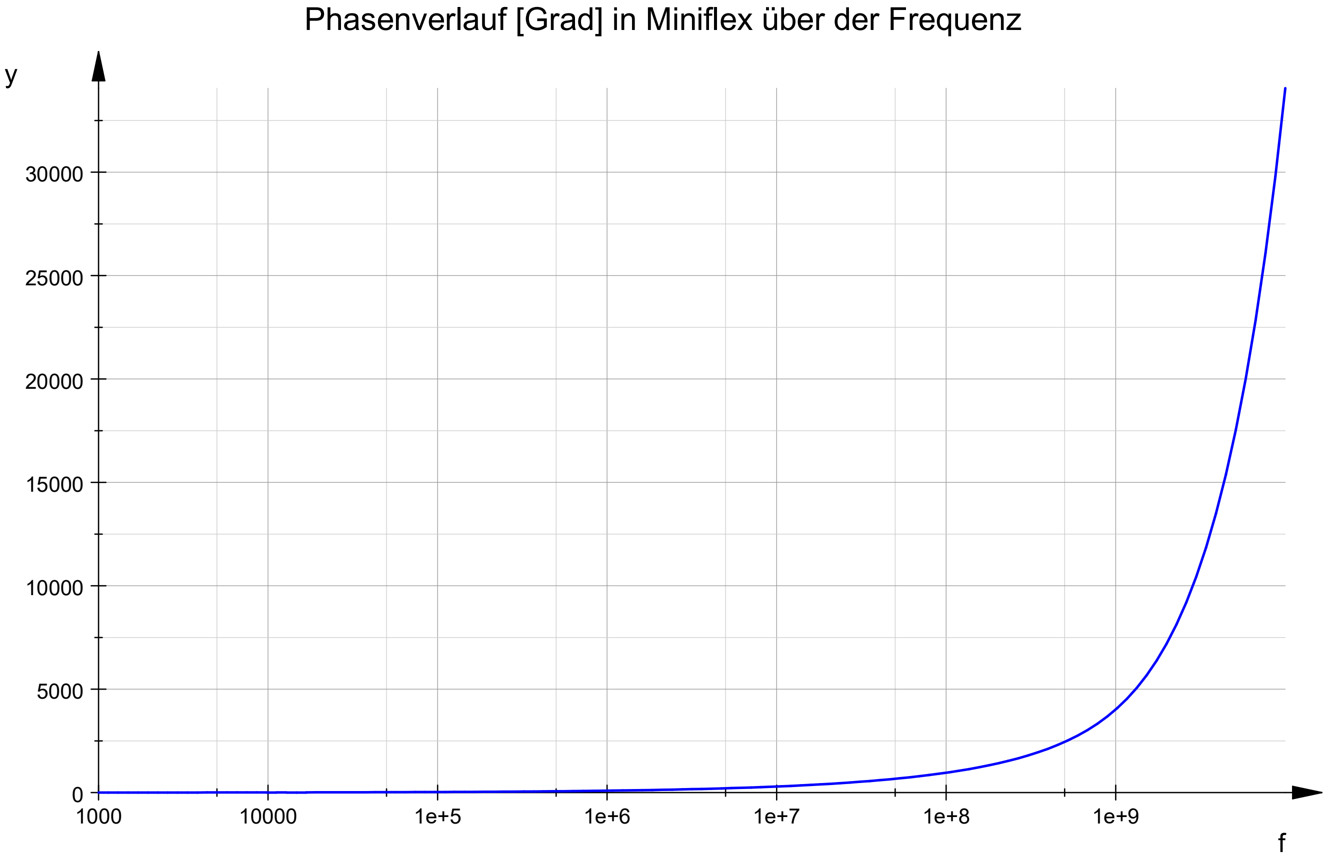
The difference to 1 is due to an inhomogeneous longitudinal wave, which results from the boundary conditions of the MAXWELL equations, but is practically of no importance here.

The calculated reflection factor 2 is purely complex, ie -j1 and describes the absorbed part of the wave.

The incident energy of the wave is thus reflected approximately half of the reflection factor 1, half absorbed by the reflection factor 2, and the rest of the energy remains in a small inhomogeneous longitudinal wave, parallel to the medium boundary.

The sample material for medium 2 to be produced from this is called here Miniflex.




Phasenverlauf [Grad] in Miniflex über der Frequenz
y
30000
25000
20000
15000
10000
5000
0
1000
10000
1e+5
1e+6
1e+7
1e+8
1e+9
f

6.0 Bibliography

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Technische Universität Budapest
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