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Transmission of EM-fields through Slots

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Abstract

This document treats the transmission of electromagnetic fields through slots. Results for different slot geometries and for slots that are filled with dielectric material, both lossless and with losses, are presented. Results for TE and TM polarisation are given. The presented results are of particular use for people working with EMC related problems since special attention is paid to different techniques to reduce the transmission.

Key Words: Chokes, Corrugations, Slot, Soft and hard surfaces

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Contents

Summary

This document contains numerical results for the transmission of electromagnetic fields through slots. Different slot geometries as well as different excitations are studied. All results are obtained with a computer code that uses the method of moments to solve the integral equations for the problem.

Two practicable methods to reduce the transmission are discussed. The first one is the common method of using conducting gaskets. In connection with this method the concept of transfer impedance is discussed and compared with results obtained by the general computer code. The second one is a method that is especially suitable for high frequencies and can be used for reduction for the TE-polarisation only. This method is based on the concept of soft surfaces.

1 Introduction

In practical structures a slot is formed whenever two parts have to be joined together. For instance, a slot is formed between the cover and the cabinet of an electronic equipment. Since the transmission of unwanted electromagnetic fields through such a slot can cause problems with electromagnetic compatibility (EMC), the analysis of the transmission is important.

This document contains numerical results for the transmission of electromagnetic fields through slots of different geometries and for different excitations. The purpose is that these results should give an insight and "feeling" for the transmission of EM-fields through slots and how the transmission can be reduced.

2 Definitions

The geometry for the problem of a slot or a gap between two perfectly conducting plates is shown in Fig. 1. The problem is two-dimensional, i.e. we have no variation along the slot axis of either the exciting field or the cross-section of the slot. The two-dimensional problem is a very good approximation of real three-dimensional cases for frequency ranges over which the slot is longer than typically 5 wavelengths.

The configuration is assumed to be excited with a plane wave on one side of the plates. The exciting field is described by its incidence angle, in the range -90 to 90 degrees, and the polarisation, either TE or TM. The polarisation is defined as TE when the electric field vector is perpendicular to the slot axis (x-axis in Fig. 1) and as TM when the magnetic field vector is perpendicular to the slot axis.

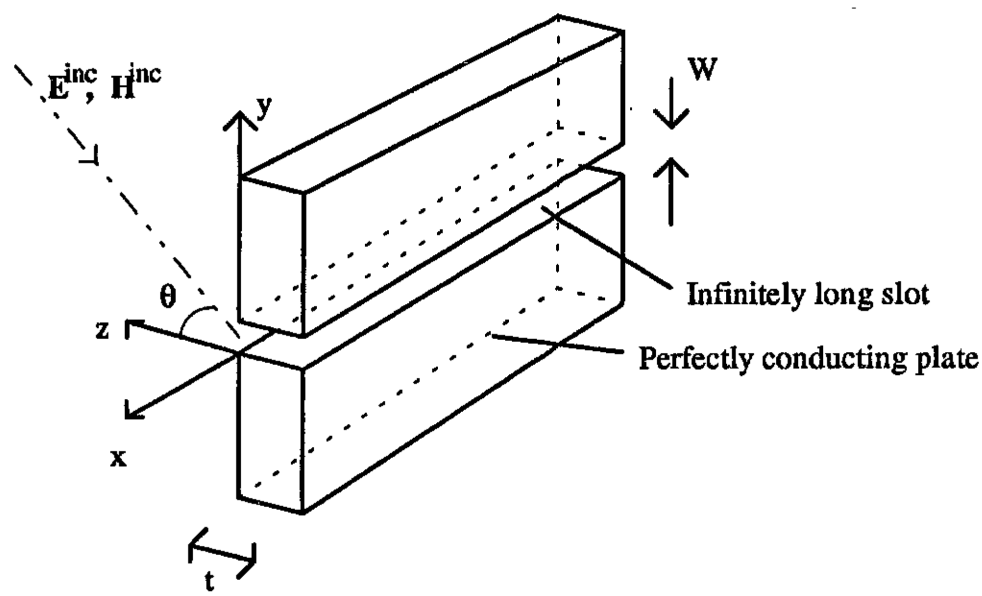

Figure 1. Slot of width W between plates of thickness t.

2.1 Transmission coefficient

The quantity that is of interest within EMC is the level of the power transmitted through the slot. Therefore, we define the transmission coefficient as the ratio of the total power transmitted through the slot per unit length along the slot to the incident power density times the slot width W. Since the exciting field is assumed to be a plane wave the transmission coefficient T can be written as:

$$T = \frac{\text{Transmitted power}}{\text{Incident power density times slot width}} = \frac{\rho}{WE_0^2} \int_{-\pi/2}^{\pi/2} \left|E(\phi)\right|^2 d\phi \qquad (1)$$

where E_0 is the incident field strength and $E(\phi)$ is the transmitted E-field at a distance ρ away from the slot. With this definition the transmission coefficient will be a measure of the attenuation of electromagnetic fields through the slot.

2.2 Analysis methods

Several simple methods are available for an approximate solution to the problem of determining the coupling of electromagnetic fields through apertures and slots. For low frequencies, i.e. when the aperture is small compared to the wavelength, the aperture can be represented by equivalent electric and magnetic dipole moments [1]. Simple formulas for the calculation of dipole moments for different forms of apertures, e.g. circular, elliptical, rectangular etc., are published in the literature, see for instance [2, Sec. 2.1.3.2.2]. This theory is often used when the effects of an EMP (ElectroMagnetic Pulse) are analysed [2]. For high frequencies, asymptotic methods such as the physical optics approximation can be used.

For a general analysis, an integral formulation based on, for instance, the equivalence principle [3, Sec. 3-5] can be used. For instance, this approach was used by Butler and Umashamkar [4] in analysing the coupling of electromagnetic fields through a slot in a ground plane of zero thickness. Auckland and Harrington take a further step for the TE-case by treating a ground plane of finite thickness [5]. Further in [6] they treat the transmission of electromagnetic fields through cascaded rectangular regions in a thick ground plane. In references [4]-[6] the method of moments [7] is used to solve the integral equation for the field distribution in the slot. Recently, Gedney and Mittra [8] treated the general case of a slot with an arbitrary cross section with a combination of the method of moments and the finite element method [9].

All results presented in this document are computed by a computer code based on an integral formulation which is solved by the method of moments [10]. A detailed description of the theories behind the code and validation of the results obtained by the code can be found in [11]. A short description of the code is found in Ch. 6.

3 Reduction of the transmission

When dealing with EMC problems, it is essential to reduce the leakage or transmission of electromagnetic fields through slots. Therefore, two different methods to reduce the transmission through slots are discussed in this chapter. The two methods are based on two entirely different concepts. The foundation of the first method is to provide a low impedance path for the induced currents between the two plates and the idea of the second method is to create a cut-off condition for the fields in the gap between the two plates.

3.1 Filling the gap with a conducting material - Transfer impedance

A common way to reduce the transmission through a slot is to fill the gap with a conducting material. The idea is to provide a low impedance path for the induced currents in the two plates. Different types of gaskets and materials suitable for this purpose have been developed over the years. Special gaskets that can provide protection against environmental effects as well as a good leakage reduction for electromagnetic fields are available.

Since the idea is to provide a low impedance path between the two plates, it is common to talk about the transfer impedance, see e.g. [12]. The transfer impedance for a gasket is in principle measured by injecting a current in the gasket and measuring the voltage drop over it. Dividing the two quantities gives the transfer impedance. In order to obtain a useable quantity the transfer impedance should be given in ohms per meter (per unit length in the transverse direction of current flow). A low frequency approximation for the transfer impedance can simply be found by measuring the DC-resistance with an ordinary ohmmeter. How far up in frequency this approximation can be used depends on the type of gasket.

When the transfer impedance is known, either given by the gasket manufacturer or by measurements, the attenuation (approx. the negative of the transmission coefficient Eq. 1) can be computed as:

$Attenuation\,[\mathrm{dB}] = 20Log\left(\dfrac{50}{Z_{tr}}\right)$ where it is assumed that the transfer impedance Z_{tr} is measured in a 50 Ω system.

It should be noted that the equation for the attenuation is valid only for the TE-polarisation. This is because the transfer impedance is measured with a current that flows in the same direction as the induced current for the TE-case.

A disadvantage of the transfer impedance concept is the frequency range over which it can be applied. Since the transfer impedance has to be measured in some type of fixture, the measurement is limited to frequencies below the first resonant mode of the fixture. For instance, the first resonant mode for the ARP-1705 [13] fixture is about 700 MHz. The transfer impedance concept also assumes that the gasket can be viewed as a single concentrated lumped impedance, this also gives a frequency limitation.

3.2 Corrugating the edges of the plates - Concept of soft surfaces

Another approach to reduce the leakage through a slot is to provide the two edges with a groove or corrugation (often called choke) with a depth of a quarter of a wavelength and a width of less than half a wavelength, see Fig. 2. Such a slot between corrugated edges is in this document referred to as a corrugated slot. By this method the soft boundary condition is also created for the TE-polarisation, see [14] and [15]. This is most easily explained by considering the choke as a conventional terminated transmission line through which the short at the bottom of the choke (the end of the transmission line) is transformed. By making the depth of the choke equal to a quarter of a wavelength, the impedance seen by the field at the top of the choke becomes infinite (open circuit) which gives the desired soft boundary condition for the TE-case, see [14] and [15]. This technique has recently been proposed in order to reduce pickup of ground noise due to scattering through slots between the reflecting panels of large reflector antennas [16]. The corrugated slot reduces the transmission for the TE-case only. The TM-case remains equally low as without the corrugations.

The technique of corrugating the edges is particular useful for high frequencies and for cases for which it is not possible to use conducting gaskets. For instance, the technique is very well suited for cabinets placed on a deck on a ship where the equipment is exposed to radar signals as well as harsh environmental influence.

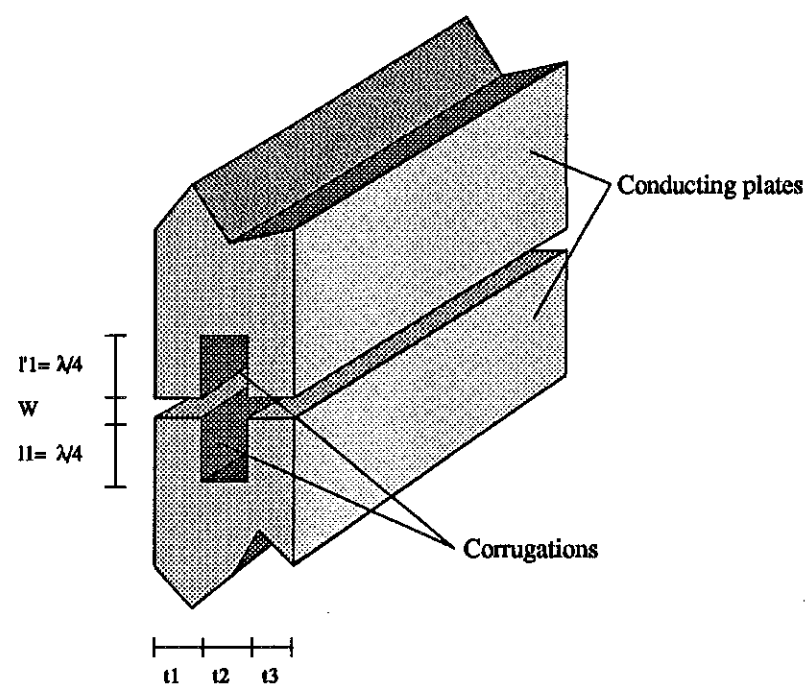

Figure 2. Corrugated slot.

4 Transmission for TE-polarisation

4.1 General observations

The TE-polarisation is the worst case in view of EMC since the transmission is high even for low frequencies. For low frequencies the transmission coefficient is roughly inversely proportional to the width of the slot and for high frequencies almost constant and equal to zero dB. This is shown in Fig. 4 where it also can be seen that the thickness of the plates is of little practical importance.

As seen in Fig. 5 the transmission coefficient is practically independent of the incidence angle for low frequencies. This is due to the fact that the transmission line mode can propagate through the slot and the excitation of this mode is almost independent of the incidence angle.

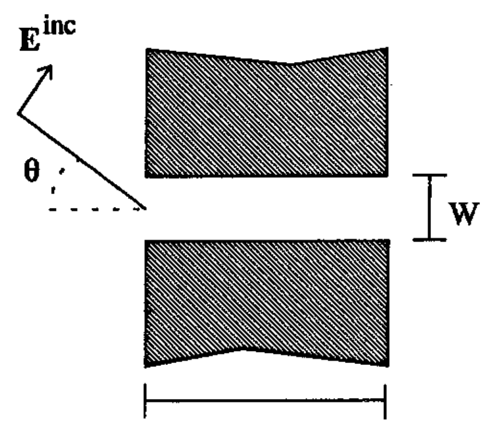

Figure 3. Cross section of a slot of width W between two plates with the thickness t.

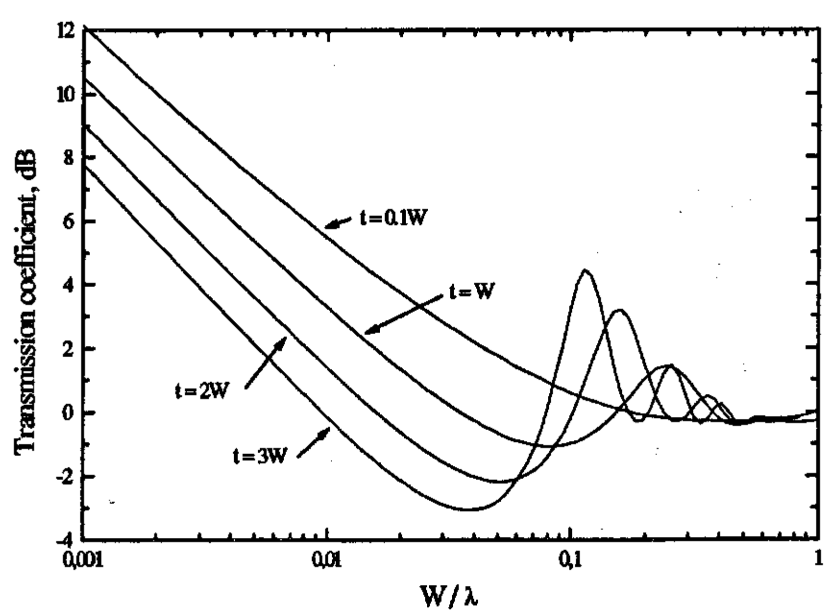

Figure 4. The transmission coefficient for the slot in Fig. 3 for different thickness of the two plates. Incidence angle θ is equal to zero, i.e. normal incidence.

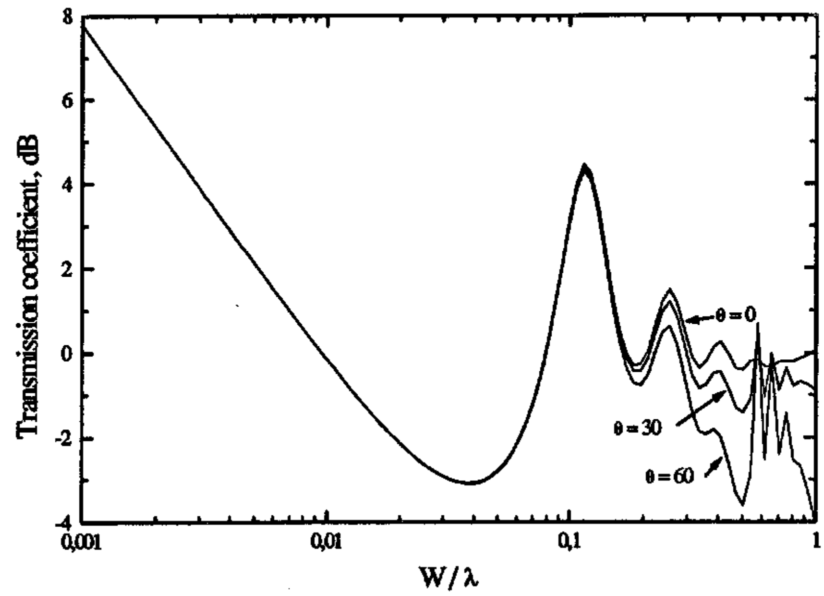

Figure 5. The transmission coefficient for the slot in Fig. 3 for different incidence angles. The thickness is equal to three times the width ($t = 3W$).

4.2 Effect of filling the gap with a dielectric material with no loss

The effect of filling the gap between the two plates with a dielectric material with no loss is shown in Fig. 6. It can be seen that the effect is that the "high frequency behaviour" is shifted toward lower frequencies and the oscillation in the transmission coefficient will be larger for a higher permittivity.

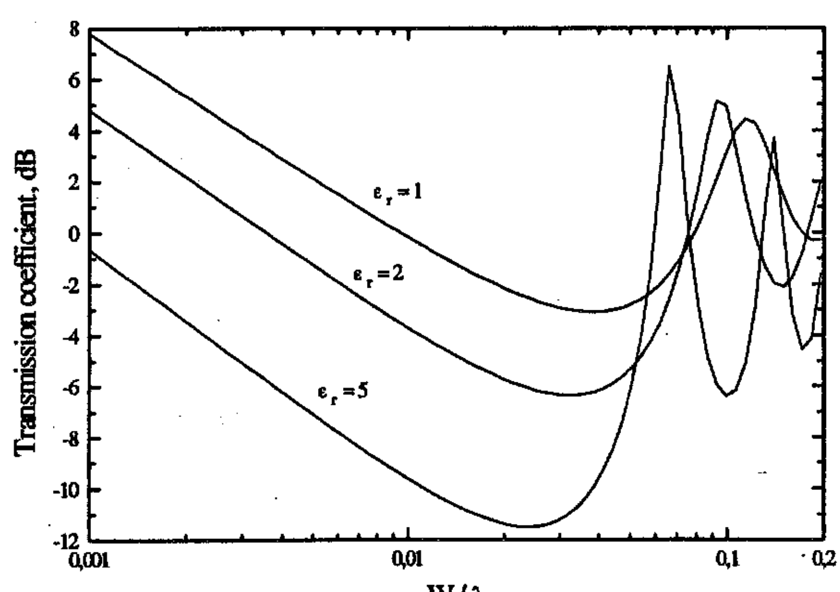

Figure 6. The transmission coefficient for the slot in Fig. 3 for different permittivity in the material filling the gap. The thickness is equal to three times the width ($t = 3W$).

4.3 Effect of filling the gap with a conducting material

The case of filling the gap between the two plates with a conducting material is interesting since it simulates the use of a conducting gasket. The concept of transfer impedance (discussed in ch. 3.1) stipulates that the transmission is proportional to the transfer impedance, i.e. inversely proportional to the conductivity of the material filling the gap. This behaviour is confirmed by the general theory as shown in Fig. 7. It can be seen that for low frequencies, the transmission coefficient is reduced by 6 dB for an increase of the conductivity with a factor of two. The difference in the transmission coefficient is 20 dB when the conductivity is changed by a factor of ten. It can also be seen that this behaviour is not true for high frequencies where the concept of transfer impedance cannot be used.

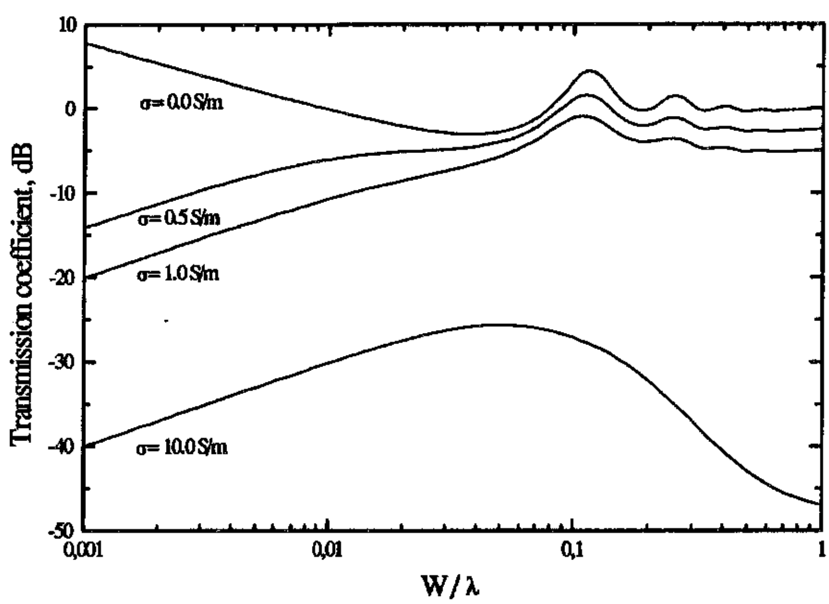

Figure 7. The transmission coefficient for the slot in Fig. 3 for different conductivities in the material filling the gap. The thickness is equal to three times the width ($t = 3W$).

4.4 Effect of corrugating the edges of the plates

As discussed in chapter 3.2 the transmission can also be reduced by introducing corrugations (or chokes) in the edges of the plates, see Fig. 2. As a first design outline the depth of the corrugations should be chosen to be equal to a quarter of a wavelength at the frequency of interest. As a consequence it is understood that this technique is most appropriate for high frequencies. Broad bandwidths for the reduction can be achieved by cascading several corrugations with different depths. Design guidelines and numerical results can be found in [17] (also in [11]).

The transmission coefficient for a corrugated slot with only one corrugation in each of the plates is shown in Fig. 8. It can be seen that the transmission coefficient has a minimum near the frequency corresponding to a corrugation depth of a quarter of a wavelength.

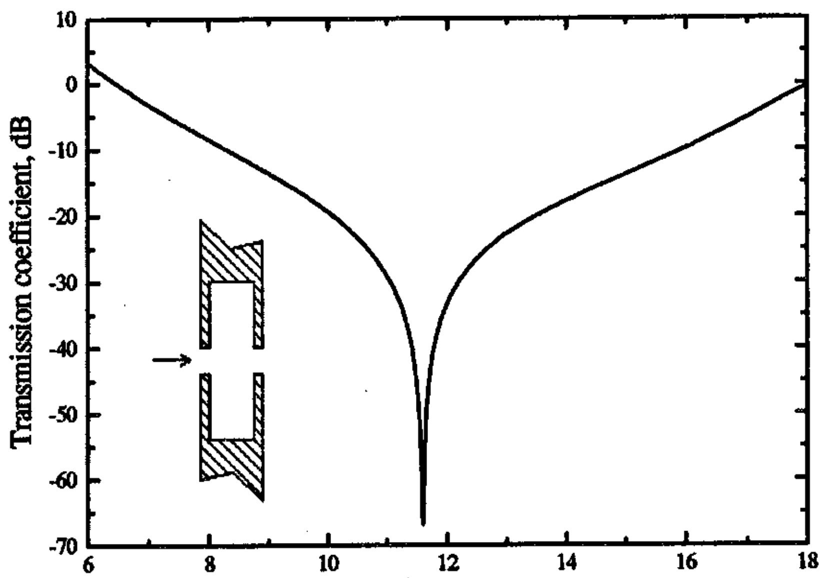

Figure 8. Transmission coefficient for a corrugated slot with one corrugation in each of the plates ($l1 = l'1 = 7.5mm$, $W = 2.8mm$, $t1 = t3 = 1.0mm$, $t2 = 5.0mm$, see Fig. 2).

The transmission coefficient for a broad band corrugated slot is shown in Fig. 9. For this example the transmission coefficient is reduced by more than 20 dB in the frequency range 8-48 GHz, compared with a slot without corrugations between plates of the same total thickness.

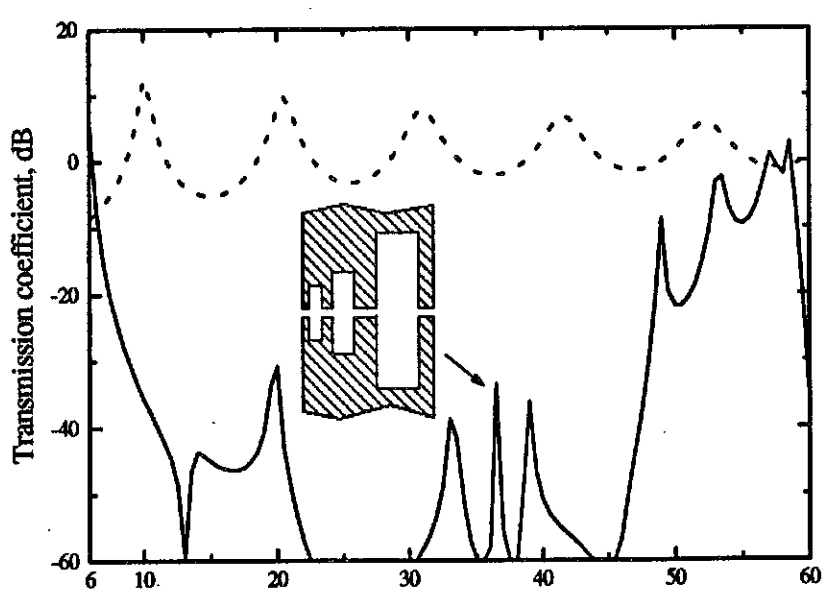

Figure 9. Transmission coefficient for a corrugated slot with three corrugations in each of the plates ($l1 = l'1 = 7.5mm$, $l2 = l'2 = 3.75mm$, $l3 = l'3 = 2.4mm$, $t1 = 1.5mm$, $t2 = 4.5mm$, $t3 = t4 = 2.25mm$, $t5 = 1.23mm$, $t6 = 1.44mm$, $t7 = 0.48mm$, $W = 0.5mm$, see Fig. 2). Dotted line represents a non-corrugated gap of $0.5mm$ in a plate of thickness $13.65mm$.

5 Transmission for TM-polarisation

5.1 General observations

The transmission coefficient is very low for the TM-polarisation if the width of the slot (W in Fig. 10) is smaller than about half a wavelength and the thickness of the plates is not too small, see Fig. 11. This is due to the fact that the electric field vector is tangential to the conducting plates in the gap and forced to be zero at the edges. This creates a cut-off condition for the field over the slot and the transmission is prevented.

In Fig. 12 it can be seen that the transmission coefficient for low frequencies is quite independent of the incidence angle, as for the TE-polarisation.

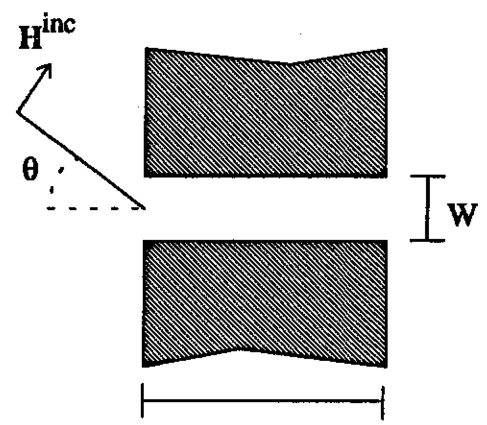

Figure 10. Cross section of a slot of width W between two plates with the thickness t.

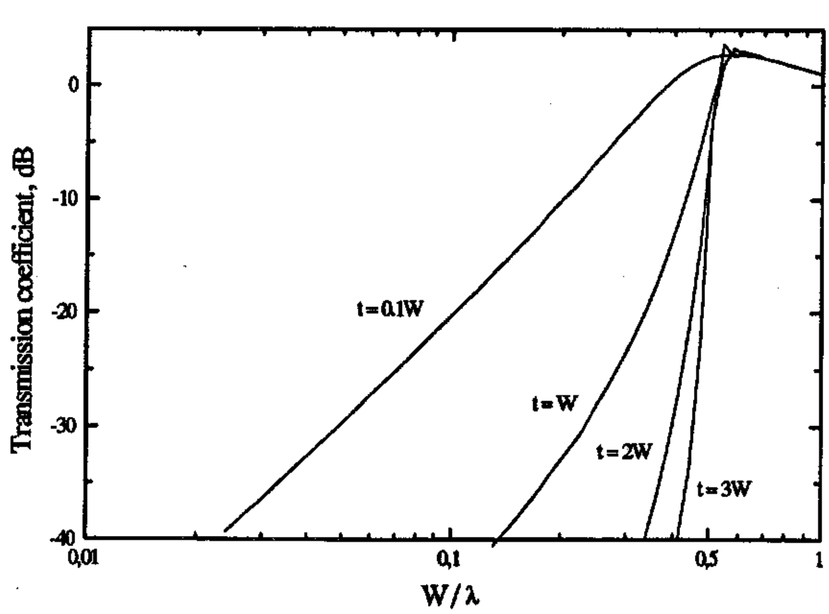

Figure 11. The transmission coefficient for the slot in Fig. 10 for different thickness of the two plates. Incidence angle θ is equal to zero, i.e. normal incidence.

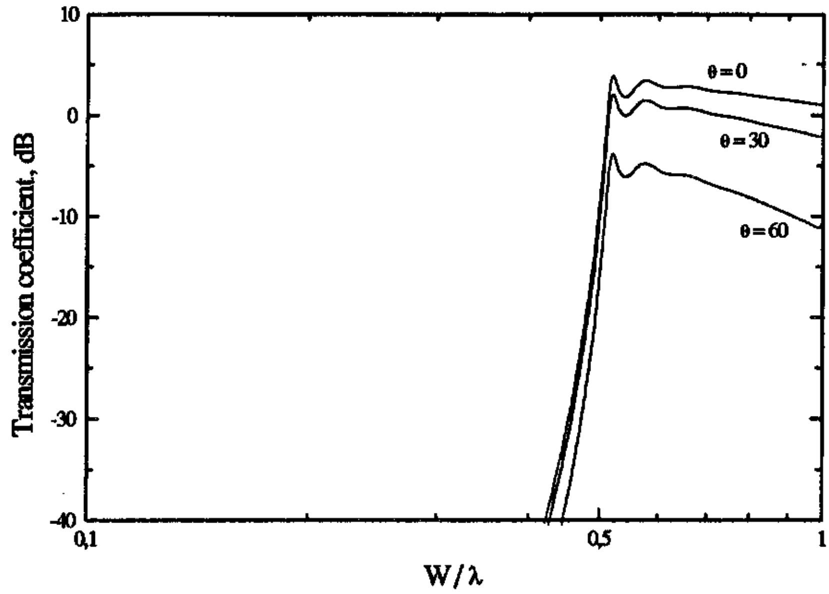

Figure 12. The transmission coefficient for the slot in Fig. 10 for different incidence angles. The thickness is equal to three times the width ($t = 3W$).

5.2 Effect of filling the gap with a dielectric material with no loss

The effect of filling the gap between the two plates with a dielectric material with no loss is shown in Fig. 13. As for the TE-polarisation, it can be seen that the effect of a higher permittivity is that the "high frequency behaviour" is shifted toward lower frequencies.

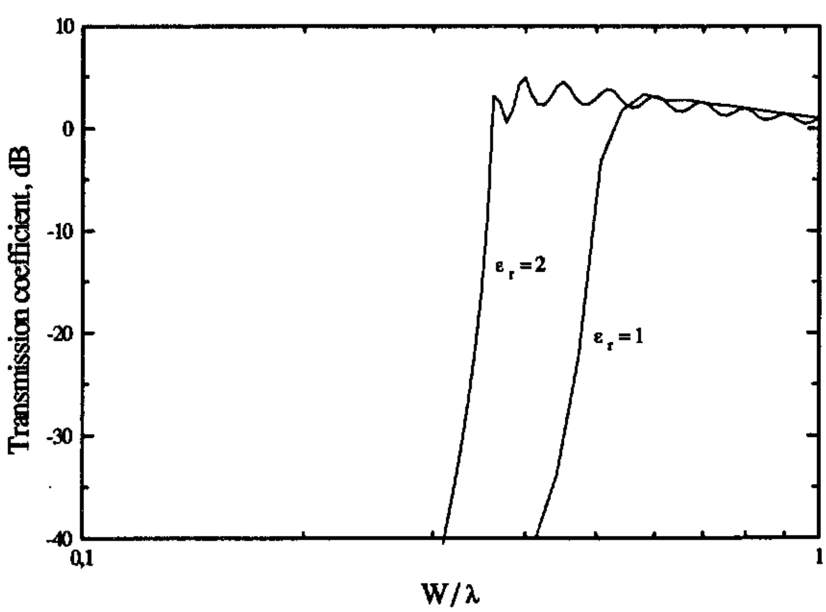

Figure 13. The transmission coefficient for the slot in Fig. 10 for different permittivity in the material filling the gap. The thickness is equal to three times the width ($t = 3W$).

5.3 Effect of filling the gap with a conducting material

As discussed in chapter 3.1 the concept of transfer impedance cannot be used for the TM-polarisation. This is verified by the results in Fig. 14 where the transmission coefficient seems to be practically independent of the conductivity for low frequencies.

Another conclusion that can be drawn from the results in Fig. 14 is that a conducting gasket will have little or no effect on the transmission for the TM-polarisation, especially for low frequencies. This also means that if a conducting gasket is used, the worst case can be changed from being the TE-polarisation to that of TM-polarisation.

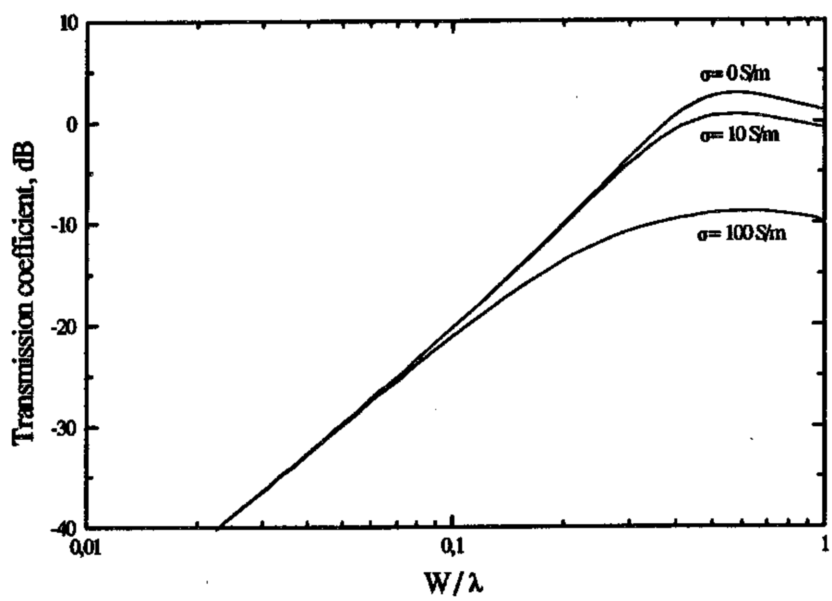

Figure 14. The transmission coefficient for the slot in Fig. 10 for different conductivities in the material filling the gap. The thickness is equal to one tenth of the width ($t = 0.1W$).

6 The computer code - SlotCalc

The Windows program SlotCalc is a general program for the calculation of the transmission of electromagnetic fields through slots and corrugated slots. All results presented in this document were computed with SlotCalc.

The geometry and material parameters for the slot together with parameters for the excitation are all defined in an input file. The input file is a standard ASCII file and can be created by a standard line editor (e.g. Windows notepad) or the special program SlotEdit. The results computed by the program SlotCalc are saved in standard ASCII files and can easily be plotted by any graphic presentation program. The calculated results are: Tangential electric field at the aperture facing the incidence side, Tangential electric field at the aperture facing the shadow side, Radiation pattern at the incidence side, Radiation pattern at the shadow side, Transmission coefficient and Reflection coefficient (defined similar as the transmission coefficient, Eq. 1). The codes SlotCalc and SlotEdit are described in detail in [10].

The code SlotCalc is based on an integral formulation of the problem of a corrugated slot consisting of an arbitrary number of cascaded rectangular sub-regions (see Fig. 2 where three sub-regions are used). A numerical solution of the field problem is obtained by the method of moments implemented as a successive inversion of the matrices associated with the tangential electric fields at the boundaries between the rectangular sub-regions forming the corrugated slot. A detailed description of the equations and how they are solved can be found in [11].

The computer codes SlotCalc and SlotEdit are available through the author.

7 References

[1] H. A. Bethe, "Theory of diffraction by small holes", Phys. Rev., Vol. 66, pp. 163-182, Oct. 1944.

[2] K.S.H. Lee, Editor, "EMP Interaction: Principles, Techniques and Reference Data", Air Force Weapons Laboratory Kirtland AFB, New Mexico, Dec. 1980.

[3] R.F. Harrington, "Time-harmonic electromagnetic fields", McGraw-Hill, inc., 1961.

[4] Chalmers M. Butler and Korada R. Umashamkar, "Electromagnetic penetration through an aperture in an infinite, planar screen separating two half spaces of different electromagnetic properties", American Geophysical Union, pp. 349-357, 1976. (also in the book "Moment Methods in Antennas and Scattering", Artech House, inc., 1990).

[5] David T. Auckland and Roger F. Harrington, "Electromagnetic Transmission Through a Filled Slit in a Conducting Plane of Finite Thickness, TE Case", IEEE Transaction on Microwave Theory and Techniques, Vol. MTT-26, No. 7, pp. 499-505, July 1978.

[6] David T. Auckland and Roger F. Harrington, "Electromagnetic Transmission Through Cascaded Rectangular Regions in a Thick Conducting Screen", AEU, Band 34, Heft 1, pp. 19-26, 1980.

[7] R.F. Harrington, "Field computation by moment methods", Macmillan New York 1968. (Reprinted by Krieger publishing company Malabar Florida 1983).

[8] Stephen D. Gedney and Raj Mittra, "Electromagnetic Transmission Through Inhomogeneously Filled Slots In A Thick Conducting Plane - Arbitrary Incidence", IEEE Trans. on EMC, Vol. 34, No. 4, pp. 404-415, Nov. 1992.

[9] P.P. Silvester and R.L. Ferrari, "Finite elements for electrical engineers", 2nd ed., Cambridge University Press, 1990.

[10] Jan Carlsson, "User Manual for SlotCalc and SlotEdit", Swedish National Testing and Research Institute, Physics and Electrotechniques, SP-AR 1993:63.

[11] Jan Carlsson, "Calculation of Transmission through Slots with Corrugations - An EMC problem", Technical report No. 159L, Department of Microwave Technology, Chalmers University of Technology, Gothenburg, Sweden, Sept. 1993.

[12] A. N. Faught, "An Introduction to Shield Joint Evaluation Using EMI Gasket Transfer Impedance Data", Proceedings of IEEE EMC Symposium 1982, pp. 38-44.

[13] ARP-1705, "Coaxial Test Procedures to Measure the RF Shielding Characteristics of EMI Gasket Materials", Aerospace Recommended Practice, Society of Automotive Engineers, Inc., June 1, 1981.

[14] Per-Simon Kildal, "Definition of artificially soft and hard surfaces for electromagnetic waves", Electron. Lett., Vol. 24, No. 3, pp. 168-170, Feb. 1988.

[15] Per-Simon Kildal, "Artificially soft and hard surfaces in electromagnetics", IEEE Trans Antennas Propagat., Vol 38, No. 10, pp. 1537-1544, Oct. 1990.

[16] Per-Simon Kildal, Lennart Steen and Peter Napier, "Reduction of scattering from gaps between reflector antenna panels by using artificially soft edges", Proceedings of IEEE AP/S Symposium 1991, pp. 1316-1319.

[17] Jan Carlsson and Per-Simon Kildal, "Transmission through Corrugated Slots", Submitted for publication in IEEE Transactions on Electromagnetic Compatibility.