$$R' = 10 \log(|T|^2) \quad (5)$$

where θ is the incidence angle, and ϕ the polarisation angle. $T_{\parallel}$ is the calculated transmission loss for an electric field parallel to the plane of incidence, and $T_{\perp}$ for an electric field normal to the plane of incidence.

Experimental results: To validate the method, a 4.7×4.7 mm metallic grid was tested. It allows transmission losses from 10 to 50 dB, the function of the frequency. With the element mounted under test, it has been verified that the field is diffuse enough to perform measurements from 400 MHz to 20 GHz.

Fig. 2 Comparison between measured and theoretical transmission loss R' for 4.7×4.7 mm metallic grid

◇ average R'
— max/min R'
— theory

Fig. 2 shows the average, the maximum and the minimum measured R' for seven different configurations of the laboratory. Those configurations correspond to different surface areas of the grid, different types of antennas, and different values of the absorption of the chambers.

The experimental results are in accordance with theory and with plane wave measurements, when all incidence angles and polarisations are taken into account (using eqns. 3–5).

The theoretical transmission loss R' of the grid has been calculated according to a numerical method [2].

Measurements of grids with other dimensions have allowed us to verify that the results only depend on the characteristics of the element under test [3]. Thus this method can be validated in the range 5–60 dB.

Conclusion: Transmission loss measurements can be performed from 5 to 60 dB, in the frequency range 400 MHz–20 GHz. This estimated measuring accuracy is ± 1 dB. This new measurement method is well suited to determine the characteristics of building components for indoor and urban radio wave propagation models, and for electromagnetic compatibility prediction models. This laboratory has allowed us to measure brick, concrete, plaster, shielded glass.

Acknowledgments: This work has been supported by the CNET: Centre National d'Etude des Télécommunications France.

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Electronics Letters Online No: 19961417

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References

- CRAWFORD, M.L.: 'Design, evaluation and use of reverberation chamber for performing electromagnetic susceptibility/vulnerability measurements', NSB Technical Note 1092, April 1986
- HILL, D.A. and WAIT, J.R.: 'Electromagnetic scattering of an arbitrary plane wave by a wire mesh with bonded junctions', *Can. J. Phys.*, 1976, **54**, pp. 353–361
- FOULONNEAU, B.: 'Mise au point d'un laboratoire de mesure de l'indice d'affaiblissement électromagnétique de composants du bâtiment'. PhD Thesis, Université de Limoges, France, October 1996

Theoretical error in the integral equation MEI

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Indexing terms: Electromagnetic wave scattering, Numerical methods, Sparse matrices, Integral equations

The theoretical, or non-numerical, error in the integral equation MEI (IE-MEI) is analysed and compared to the numerical error in the method of moments (MoM). It is found that, although this error does not decrease with the discretisation step, it is smaller for the usual discretisation than the error in the MoM.

Introduction: The measured equation of invariance (MEI) was introduced by Mei *et al.* [1] as an efficient technique for numerically deriving the mesh truncation coefficients in finite difference and finite elements methods [2]. Recently, the MEI technique has been used to find the matrix coefficients of an approximate sparse matrix boundary element method, in which the unknowns only appear on the scatterer boundary [3, 4]. This new approach was called the integral equation formulation of the MEI (IE-MEI). In this Letter we study the error in the surface current computation by the IE-MEI technique and compare it with the error of the well-established method of moments (MoM).

IE-MEI: For two-dimensional perfectly electrically conducting (PEC) scatterers, a linear relationship can be established between the tangential components of the electric and magnetic scattered fields, E^s and H^s , at M neighbouring nodes in the boundary of the scatterer, of the form

$$\sum_{m=n-\frac{M-1}{2}}^{n+\frac{M-1}{2}} (a_{nm}E_m^s + b_{nm}H_m^s) = R_n \simeq 0 \quad n = 0, \dots, N-1 \quad (1)$$

where N is the total number of boundary nodes. This equation is valid for both the transverse-magnetic (TM) and the transverse-electric (TE) cases, with different a_{nm} , b_{nm} coefficients.

In the IE-MEI, these coefficients are obtained by the MEI procedure [1, 3, 4]. For convex scatterers, numerical experience has shown that the residual R_n in eqn. 1 approaches zero with decreasing mesh size h . Eqn. 1 may be concisely expressed in matrix form as

$$[A_{nm}][E_m^s] + [B_{nm}][H_m^s] = [R_n] \simeq 0 \quad (2)$$

where $[A_{nm}]$ and $[B_{nm}]$ are cyclic M -diagonal matrices. Substitution of the PEC boundary conditions $E^s = -E^i$ and $J^s = H^i + H^s$ in eqn. 2, where E^i and H^i denote the incident electric and magnetic fields, and neglecting the residual, results in

$$-[A_{nm}][E_m^i] + [B_{nm}](\bar{J}_m^s - [H_m^i]) = 0 \quad (3)$$

where $[\bar{J}_m^s]$ is an approximation to the induced current. From eqn. 3, we obtain

$$[\bar{J}_m^s] = [H_m^i] + [B_{nm}]^{-1}[A_{nm}][E_m^i] \quad (4)$$

Theoretical error: The theoretical error in the induced current, in eqn. 4, resulting from neglecting the residual in eqn. 2, is readily shown to be

$$[\Delta J_m^s] = [J_m^s] - [\bar{J}_m^s] = [B_{nm}]^{-1}[R_n] \quad (5)$$

where $[J_m^s]$ is the discretised exact current. The residual in eqn. 5 may be expressed as [3, 4]

$$[R_n] = [E_{nm}][J_m^s] \quad (6)$$

where the elements of the matrix $[E_{nm}]$ are given as

$$E_{nm} = \sum_{i=n-\frac{M-1}{2}}^{n+\frac{M-1}{2}} [a_{ni}G_{EJ}(\vec{p}_m, \vec{p}_i) + b_{ni}G_{EM}(\vec{p}_m, \vec{p}_i)] \quad (7)$$

Here, G_{EJ} and G_{EM} are the electric field Green's functions for the electric and magnetic currents, respectively, and $\vec{p}_m$, $\vec{p}_i$ are the vector positions of nodes m and i . It should be noted that eqn. 7 is analogous to the null field introduced in [5] for the original MEI [1].

We note from eqn. 5 that although the residual $[R_n]$ converges to zero when the mesh spacing h decreases, $[\Delta J_n^s]$ may not decrease if the norm of $[B_{nm}]^{-1}$ increases at the same, or a higher, rate. This is illustrated for a circular cylinder in Fig. 1, which shows the behaviour of these variables against the discretisation step size h/λ , where λ is the wavelength. The average error in the induced current has been computed as $\Sigma_n |J_n^s - J_n^a|/N$. Observe that the error in the MoM current decreases as h/λ , while the error in the IE-MEI current converges to a constant. In both methods the integral equations have been discretised by the delta function basis expansion and testing, except for the self-impedance terms, where pulse basis and small argument approximations of the Green's functions have been used.

Fig. 1 Average error in induced current for a PEC circular cylinder of unit radius excited by a TM plane wave, against normalised mesh size

Also shown are the 2-norms of $[R_n]$ and $[B_{nm}]^{-1}$
 —×— MoM error
 —○— IE-MEI error
 — 2-norm of $[R_n]$
 - - - 2-norm of $[B_{nm}]^{-1}$

The 2-norm of the matrix $[B_{nm}]^{-1}$ and the norm of the residual $[R_n]$ have also been plotted. The latter has been normalised by $N^{1/2}$ to remove the dependence on the number of nodes. Note that in this example, the normalised residual norm decreases as $(h/\lambda)^2$, while the norm of $[B_{nm}]^{-1}$ increases as $(h/\lambda)^{-2}$, thus preventing the decrease of the induced current error (eqn. 5). This behaviour is analogous to that observed in [6] for the original MEI [5].

Fig. 2 Magnitude of error in induced current for PEC circular cylinder of unit radius excited by a TM plane wave

— IE-MEI with $h = \lambda/10$
 - - - MoM with $h = \lambda/10$
 . . . MoM with $h = \lambda/40$

It is remarkable that although the IE-MEI error converges to a constant as h/λ decreases, for $h > \lambda/60$ it is smaller than the numerical error in the MoM. Furthermore, for the usual choice of $h = \lambda/10$ the IE-MEI error is similar to the MoM error for $h = \lambda/40$. To illustrate, Fig. 2 compares the IE-MEI error for $h = \lambda/10$ with the MoM error for $h = \lambda/10$ and $h = \lambda/40$.

In conclusion, we have shown that the theoretical error in the IE-MEI current, which arises from neglecting the residual in eqn. 2, does not vanish as the mesh size h goes to zero. This is in spite

of the fact that for convex shaped scatterers, the residual decreases for decreasing h . Nevertheless, our experience has shown that for typical discretisations, the IE-MEI error is smaller than the error in the MoM.

Acknowledgments: This work has been partially supported by the Spanish 'Comisión Interministerial de Ciencia y Tecnología' (CICYT) under project TIC 95-0983. The 'Dirección General de Investigación Científica y Enseñanza Superior' (DGICYES) has supported the sabbatical leave of J.M. Rius at the École Polytechnique Fédérale de Lausanne (EPFL), Switzerland, under grant PR95-331.

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24 September 1996

Electronics Letters Online No: 19961450

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References

- 1 MEI, K.K., POUS, R., CHEN, Z., LIU, Y.W., and PROUTY, M.D.: 'The measured equation of invariance: a new concept in field computations', *IEEE Trans. Antennas Propag.*, 1994, **42**, (3), pp. 320-327
- 2 STUPFEL, B., and MITTRA, R.: 'A theoretical study of numerical absorbing boundary conditions', *IEEE Trans. Antennas Propag.*, 1995, **43**, (5), pp. 478-487
- 3 RIUS, J.M.: 'Integral formulation of the measured equation of invariance', *Electron. Lett.*, 1996, **32**, (1), pp. 23-25
- 4 RIUS, J.M., POUS, R., and CARDAMA, A.: 'Integral formulation of the measured equation of invariance: a novel sparse-matrix boundary element method', *IEEE Trans. Magn.*, 1996, **32**, (3), pp. 962-967
- 5 JEVTIC, J.O., and LEE, R.: 'A theoretical and numerical analysis of the measured equation of invariance', *IEEE Trans. Antennas Propag.*, 1994, **42**, (8), pp. 1097-1105
- 6 JEVTIC, J.O., and LEE, R.: 'An analytical characterization of the error in the measured equation of invariance', *IEEE Trans. Antennas Propag.*, 1995, **43**, (10), pp. 1109-1115

Thermionic field emission in p-barrier enhanced InP/InGaAs/InP HEMTs

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Indexing terms: Thermionic emission, High electron mobility transistors

A model for thermionic field emission in p-barrier enhanced InP HEMTs is presented indicating that a reduction in the gate leakage of those devices is related to an increase in effective barrier thickness. Good agreement between this model and our experimental data is obtained.

Introduction: Owing to the successful development of high electron mobility transistors (HEMTs) in the last few years for mm-wave applications, much attention has been spent on the gate leakage mechanisms of these devices. Thermionic field emission is known to be the dominating process at room temperature for low drain bias [1, 2].

To avoid aluminium related problems such as aging, oxidation or selective etching of the gate recess, efforts have been made to replace all AlInAs layers in conventional InP based HEMT structures by InP. These devices exhibit excellent RF performance [3, 4]. Because of the low Schottky barrier height on unintentionally undoped InP ($\Phi_B \approx 0.45\text{eV}$) an additional p-doped InP layer is used to enhance the barrier [5].

By a simple modification of the thermionic field emission theory, we demonstrate that the reduction of gate leakage through p-barrier enhanced Schottky contacts is related to an increase in the