



RADIO SCIENCE FOR HUMANITY

Microwave transmission and crosstalk variations for two lines on a PCB induced by partially reverberating environment *Influence d'un milieu partiellement réverbérant sur la transmission micro-ondes via deux lignes imprimées et sur leur diaphonie*

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Abstract:

We measure the effect of a partially reverberating environment on the crosstalk of two imprinted lines on a printed circuit board (PCB). The PCB is placed within an aluminium cavity with low quality factor $Q \approx 500$ and the ends of the lines are attached to a four port network analyzer. We find that the reflection and transmission of the excited line of the open cavity correspond to those of the closed cavity except in the vicinity of its resonances. Indeed, close to the resonances, the discrepancies can be large and a modified crosstalk is observed. Additionally we compare our results with simulations using the methods of moments (MoM) which are in good agreement with our experimental results. Moreover, these simulations give access to the current densities on the lines, which also show perturbed patterns.

Résumé:

Nous étudions expérimentalement l'effet d'un environnement partiellement réverbérant sur la diaphonie entre deux lignes imprimées sur PCB (Printed Circuit Board). Le PCB est disposé dans une cavité en aluminium de faible coefficient de surtension ($Q \approx 500$). Les deux lignes sont connectées aux ports d'un analyseur de réseau vectoriel quatre ports. On met en évidence que réflexion et transmission sont insensibles à la présence des parois de la cavité sauf au voisinage des résonances de cette dernière, où la diaphonie peut être considérablement modifiée. Une simulation électromagnétique appropriée développée pour ce travail à partir d'une méthode de moment reproduit fidèlement les observations expérimentales. En outre, ces simulations fournissent les densités de courant des lignes, qui présentent des structures spatiales perturbées.

1 Introduction

Nowadays, integrated circuits are used to control medical devices, airplanes, cars, security controls, etc. They are one of the main ingredients of our daily life and their functionality is crucial to our lives today. Typically they are based on printed circuit boards (PCB) with several lines next to each other, often in parallel. Due to the increasing demand of high data rates, the operating frequencies are increasing further and further leading to higher crosstalk [1, 2]. Signal integrity, a necessity for the functioning of devices, is severely attacked by crosstalk [3], leading to problems in high-speed PCB designs [4, 5, 2] with additional problem of electromagnetic interferences (EMI) and electromagnetic compatibility (EMC) as well [6]. One possibility to reduce crosstalk is to place a ground plane close to the lines [7] or by additional separating grounded lines [8, 9]. Until now most investigations concentrated on PCBs in free space. In this paper we show that due to a partly reverberating environment, where the grounded plane is one part of the environment, crosstalk can be increased or reduced by several dB. We show this experimentally using two parallel lines and investigate the crosstalk by detailing numerically the electromagnetic field structure within the reverberating environment.

2 Experimental setup

The experimental setup is shown in figure 1. Two copper lines are printed on a PCB of length $a = 19.9$ cm separated by a distance of $d = 1.8$ cm. Their width is 2 mm and their thickness is negligible (for details refer to figure 1(a)). The board is placed in a dural-aluminum box, where SMA connectors (Huber & Suhner) leading

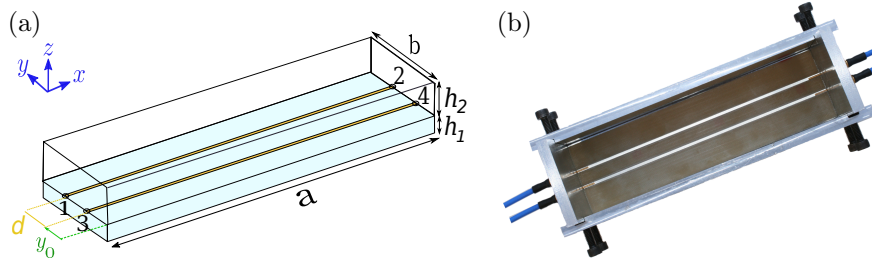


Figure 1 – (a) Sketch of the experimental setup showing the two lines printed on a PCB with length $a = 19.9$ cm with a distance of $d = 1.8$ cm from each other and of $y_0 = 3.47$ cm to the boundary. The height of the backgrounded PCB is $h_1 = 1.6$ mm with $\epsilon_r = 4.47$ and $\tan \delta = 0.027$. The aluminum cavity has a length $l = 20$ cm, width $b = 5.62$ cm and a height $h_2 = 4$ cm. Line A is connecting port 1 to port 2 and line B is connecting the other ports. (b) Photograph of the setup without top, corresponding to the open cavity.

the signal through 2 mm air holes drilled in the side wall. The connectors are in contact with the printed lines and are attached to a 4-port vector network analyzer (VNA, Agilent E5071C). The box dimensions and the characteristics of the PCB are detailed in figure 1(a) and a photograph of the open system is shown in (b). We excite line A (often also called the aggressor or feed line) via port 1 and measure the reflection S_{11} and transmission S_{21} as well as the crosstalk S_{41} to line B (often also called victim line) in the frequency range from 1 to 5 GHz.

Additionally we performed calculations using the method of moments (MoM) to determine the currents on the lines as well as the fields within the cavity [10]. In the present work, our MoM approach describes the currents on the lines by decomposing them on the transverse modes of two waveguides of finite lengths (here the heights h_1 and h_2) and different permittivities. The input parameters are therefore: the geometric description of the two lines, the transverse dimensions of the waveguides, their heights and their complex permittivities. Here, the waveguide of height h_2 is filled with an artificial dielectric material with the permittivity of air and an adjustable loss tangent to account for the observed overall quality factor of the system. The excitation is obtained by imposing a uniform electric field on a small area at each end of the excited line. Apart from the impedances of the lines which are calculated by our MoM approach, an extra impedance Z_{ref} , smoothly depending on the frequency, is introduced to deduce the S parameters at the four ports.

3 Discussion

3.1 Transmission and Reflection

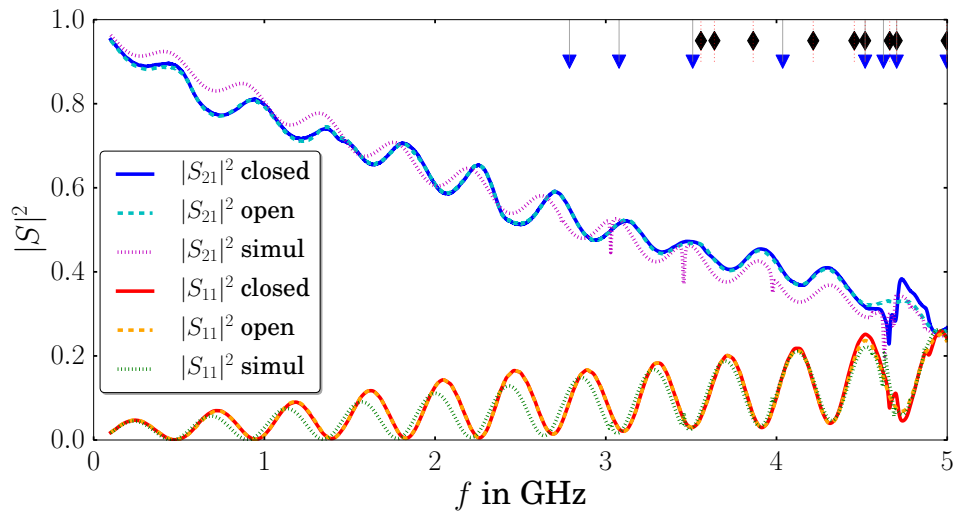


Figure 2 – Transmission $|S_{21}|^2$ and reflection $|S_{11}|^2$ for the excited line A for the closed cavity with height $h_2 = 4$ cm (solid line) and without top, i.e., open cavity (dashed line). The triangles (diamonds) mark TM(TE)-modes of an empty perfect conducting rectangular cavity with the same dimensions. The numerical simulations for the closed cavity using the MoM is shown in dotted.

The results for the closed cavity with height $h_2 = 4$ cm and for the open cavity are compared. In figure 2 the reflection S_{11} and transmission S_{21} of line A are presented. Additionally the theoretical TM-modes (z-

component of the magnetic field is 0) and TE-modes (z-component of the electric field is 0) for a rectangular box with length $l = 20$ cm, width $w = 4.54$ cm and a height $h_{eff} = h_2 + \sqrt{\epsilon_r} h_1$ cm are shown. Note, that we neglected the slight breaking of the symmetry due to the two lines and the discontinuity at the air PCB interface. In the frequency range below the first resonances, the S parameters are nearly indistinguishable between the open and closed cavity. For the low lying resonances still a good agreement is found but at higher frequency (e.g. around 4.6 GHz) important discrepancies are observed experimentally.

The numerical simulations using MoM are presented in figure 2 by the dotted lines and are in overall agreement with the experiments. They show additionally sharp peaks at the low lying TM resonances, but also strong deviations from the open case at higher frequencies. To obtain the observed experimental loss of the cavity ($Q \approx 500$) we used a volumic loss tangent for the air ($\tan \delta = 1/500$) in the simulations. This simulations do not take into account the variation of quality factors coming from the mode profiles. Increasing the volumic loss, i.e., reducing the quality factor for the low lying resonances make them vanish as well, but we fixed the values to get a better agreement at the higher lying resonances.

3.2 Experimental Results on Crosstalk between Lines

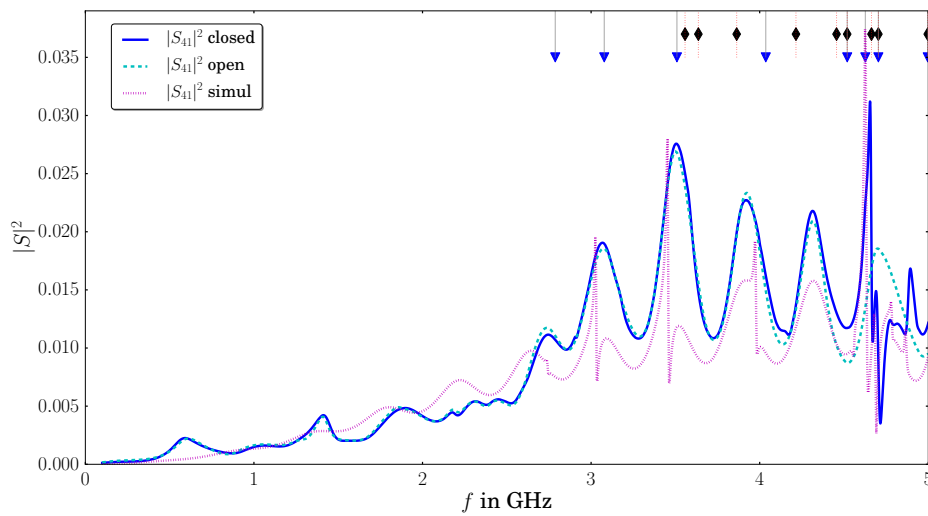


Figure 3 – The crosstalk from the excited line A to line B (S_{41}). The triangles (diamonds) mark TM(TE)-modes of an empty perfect conducting rectangular cavity with the same dimensions. The numerical simulations for the closed cavity using the MoM is shown in dotted.

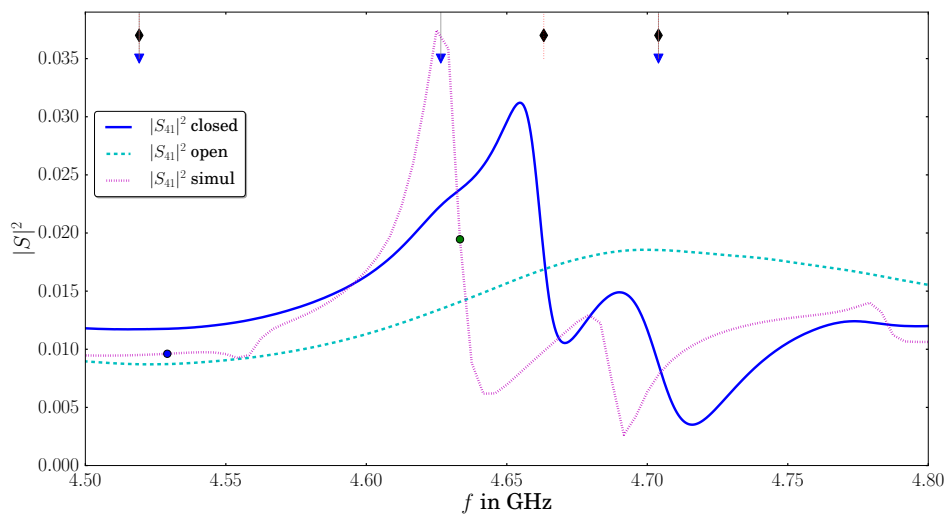


Figure 4 – Zoom of the crosstalk (see figure 3) on the TM and TE resonances. Solid, dashed and dotted lines correspond to the closed, open cavities and the simulation, respectively (as in figure 3). The red and blue filled circles on the numerical curve correspond to the frequencies where the currents on the lines are presented in figure 5.

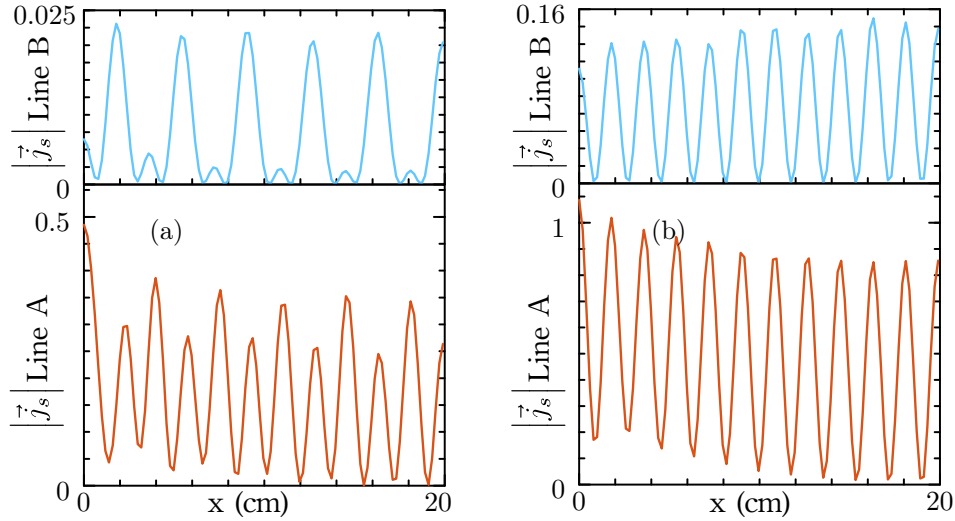


Figure 5 – The simulated surface current density $|\vec{j}_s|$ using the MoM for an excitation by port 1 (see figure 1) (a) at cavity resonance frequency (4.633 GHz) and (b) apart (4.52 GHz). The frequencies are indicated in figure 4 by filled circles on the dashed curve.

Now we concentrate on the crosstalk, i.e., the transmission from port 1 to port 4 (S_{41}) also called the forward crosstalk. The whole measured frequency range is shown in figure 3. Again in the lower lying frequency range no difference is seen between the open and the closed measurement. But the difference in the higher frequency regime is even more pronounced in the crosstalk than in the reflection or transmission of line A. Again the numerical data show an overall agreement notwithstanding the presence of sharp peaks for the low lying resonances. They also vanish once reducing the quality factor of these modes.

To detail the deviations induced by the partly reverberant cavity we present in figure 4 only the frequency range from 4.5 to 4.8 GHz. We fitted two complex Lorentzians to the complex S_{41} parameter. The eigenfrequencies are at 4.66 GHz and 4.704 GHz and their width is about 7.5 MHz and 19 MHz (quality factors of $Q = 620$ and $Q = 245$), respectively. The deviations observed in the crosstalk between the open and closed cavity can be as large as +6 dB and -3 dB even though the environment is not strongly reverberating. Thus this effect is not at all negligible and should be taken into account if PCBs are placed in such environments. The numerical simulations resemble the same structure though a bit shifted due to the sensitivity on the geometrical parameters. It allows us to calculate the current densities on the lines as well, where we have no experimental access.

The currents [see figure 5(a,b)] of closed cavity is at resonance (4.633 GHz) and off resonance (4.52 GHz). First the overall current is reduced at the cavity resonance frequency (note the change of scale) and secondly a spatial variation of the currents on the excited line A and the induced currents on line B is observed, corresponding to the discrepancies found for the S parameters. These discrepancies already show that a pure deterministic treatment might not be well adjusted to the problem, but a statistical one taking into account possible variations of the environment seems to be more appropriate. To this aim, predictions from random matrix theory [11, 12] and their embedding in the electromagnetic frame using chaotic reverberation chambers [13] is useful. Here we will concentrate on the deterministic part to get more insights on how the coupling is taking place. For this, we now allow ourselves to vary the height parameter h_2 to obtain a better agreement between the numerical and experimental crosstalk.

3.3 Detailed Numerical Results

To obtain the better agreement seen in figure 6 we reduced the previously used height h_2 by 1% and the quality factor to $Q = 350$. The MoM allows us to calculate all components of the electric E and magnetic H fields within the cavity. Cuts of the xy -plane at two different heights for the six field components are shown in figures 7 and 8, respectively. The first column corresponds to the x component and the central and right columns to the y and z components respectively. The odd rows show the field components directly above the PCB (0.2 mm above), i.e., the two lines, whereas the even rows show them well above the PCB (32 mm above). The first two rows are for the ν_0 frequency, the next two rows for ν_{max} and the last two for ν_{min} . In the odd rows the evanescent field of the currents on the lines are still visible and the field due to the cavity resonance is often suppressed. For the even rows, it is just the other way around.

To see the coupling induced via the resonances of the reverberating environment, we calculated the eigenmodes of the lossless cavity (neglecting Ohmic losses at walls and the loss tangent of the PCB) corresponding to the adjusted problem, taking into account the PCB with its relative electrical permittivity ϵ_r using COMSOL. The

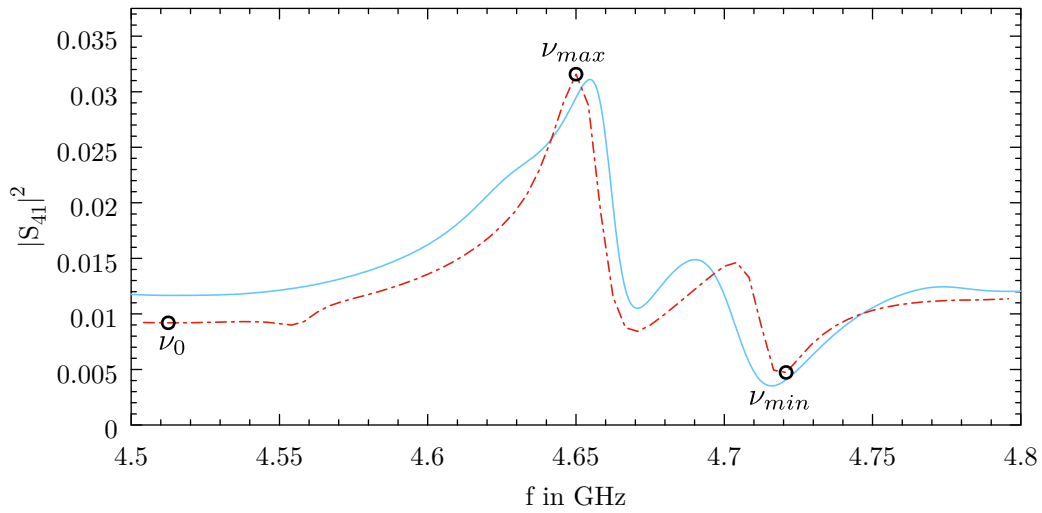


Figure 6 – Experimental crosstalk $|S_{41}|^2$ with numerical results where the parameters were adjusted. The frequencies for the mode decomposition are marked and given by $\nu_0 = 4.516$ GHz, $\nu_{max} = 4.650$ GHz, and $\nu_{min} = 4.721$ GHz,

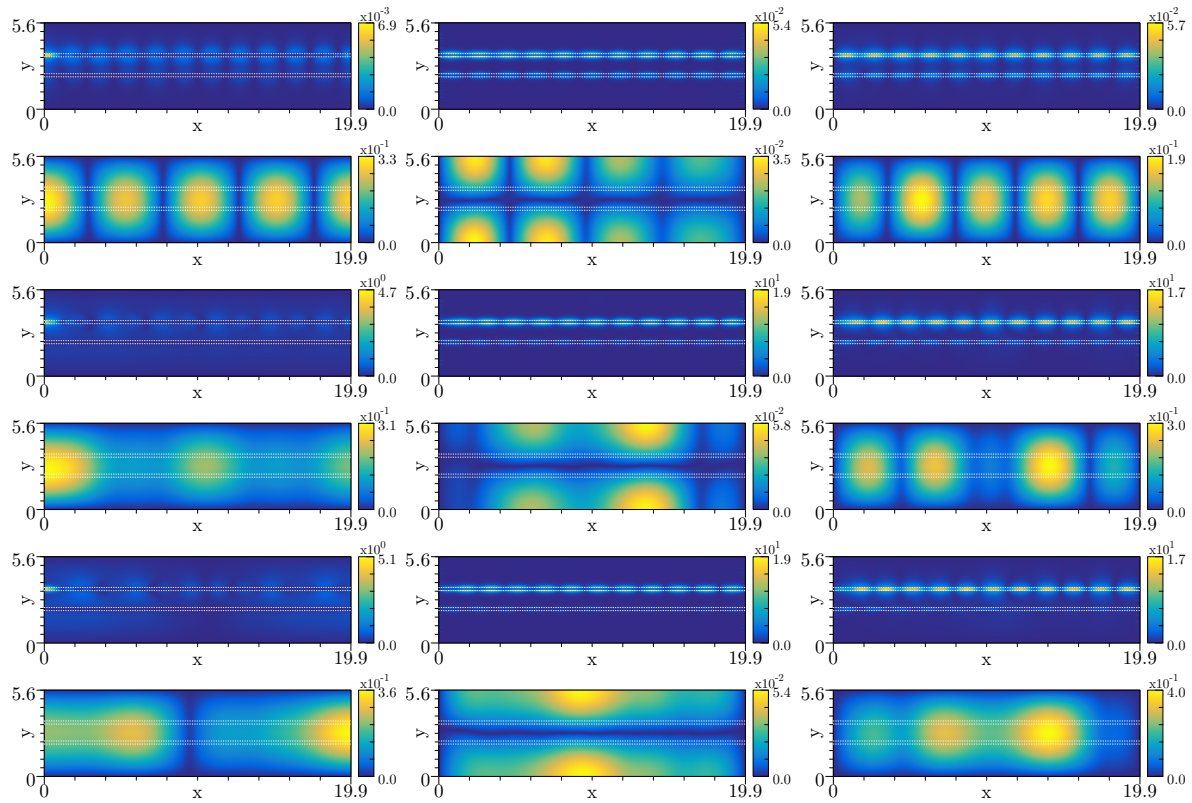


Figure 7 – Electric field components E_x (left column), E_y (centre column), and E_z (right column) for the three different frequencies at ν_0 , ν_{max} , and ν_{min} for two different x, y -planes at heights $a_{p1} = 0.2$ mm and $a_{p2} = 32.0$ mm above the two transmission lines. Note that the first plane is very close to the transmission lines, whereas the second is closer to the top plate. For each pair of rows, the vector fields are normalized by the mean value of their norms averaged over the volume.

eigenfrequencies, their approximate mode structures (TM/TE) and the corresponding mode numbers are given in table 9. In figure 10 the decomposition of the field obtained by MoM on the eigenmodes at the three different frequencies ν_0 (a), ν_{max} (b), and ν_{min} is shown. In the case of the maximal and minimal deviations of the crosstalk, the magnetic field is dominated by the lowest TM mode, whereas the electric field is dominated by the closest eigenmodes. This suggests that the coupling between the two lines is of magnetic type and is induced by the cavity. In contrast, in the case of ν_0 , the magnetic and electric fields are equally dominated by the closest eigenmode (TM 510). Under which circumstances the crosstalk is increased or decreased needs to be further

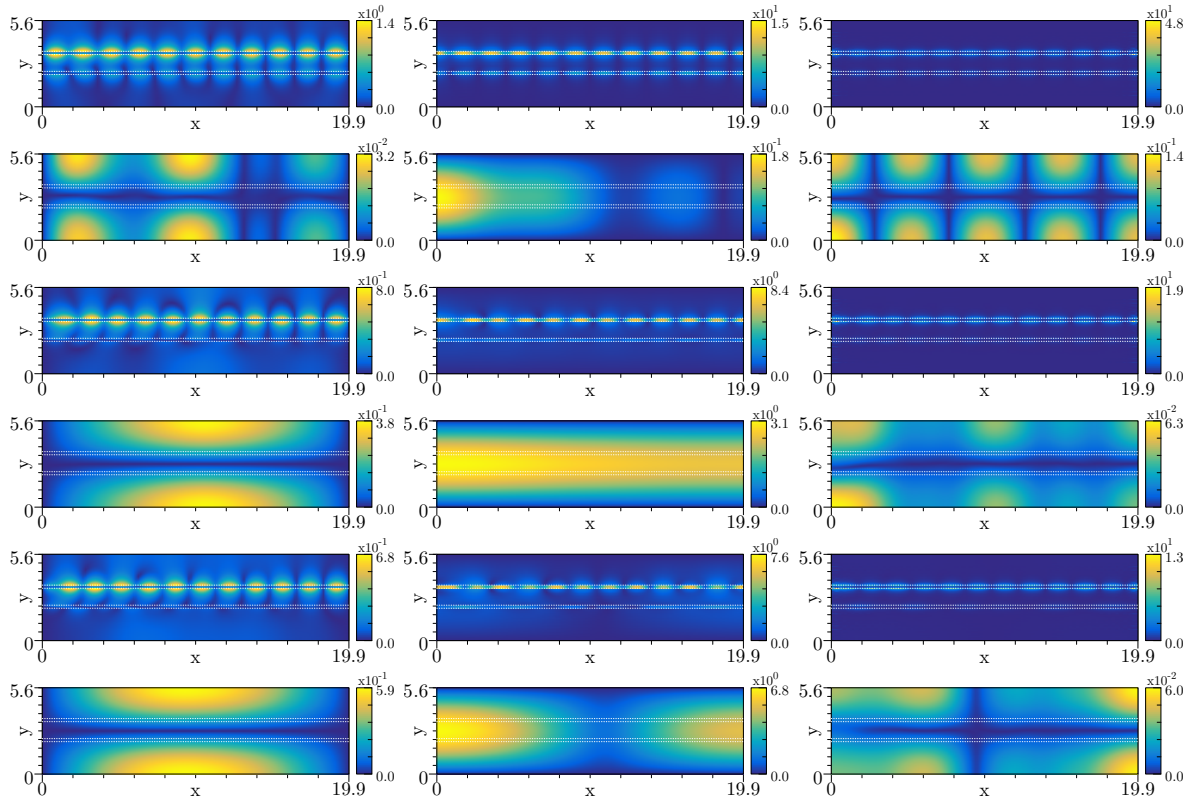


Figure 8 – Same as figure 7 but for the magnetic fields.

f_n/GHz	2.741	3.026	3.449	3.837	3.965	4.053	4.388	4.541	4.620	4.630	4.680	4.799	4.819
Mode	TM	TM	TM	TE	TM	TE	TE	TM	TE	TM	TE	TM	TE
n_x, n_y, n_z	110	210	310	101	410	201	301	510	011	111	111	211	401
4.859	5.069	5.142	5.157	5.313	5.322	5.423	5.464	5.514	5.706	5.798	5.848	5.879	5.959
TE	TM	TE	TM	TM	TE	TM	TM	TE	TM	TM	TM	TE	TE
211	311	311	610	120	501	411	220	411	320	710	511	601	511

Table 9 – Eigenfrequencies (in GHz) of the rectangular lossless cavity (refined values obtained by the fitting) including the substrate of the PCB but without the two lines. The modes have been calculated using COMSOL and the general mode structure is indicated by TM (electric field mainly in z direction) and TE (magnetic field mainly in z direction). The mode numbers in the x , y , and z directions are given by the triplets n_x, n_y, n_z .

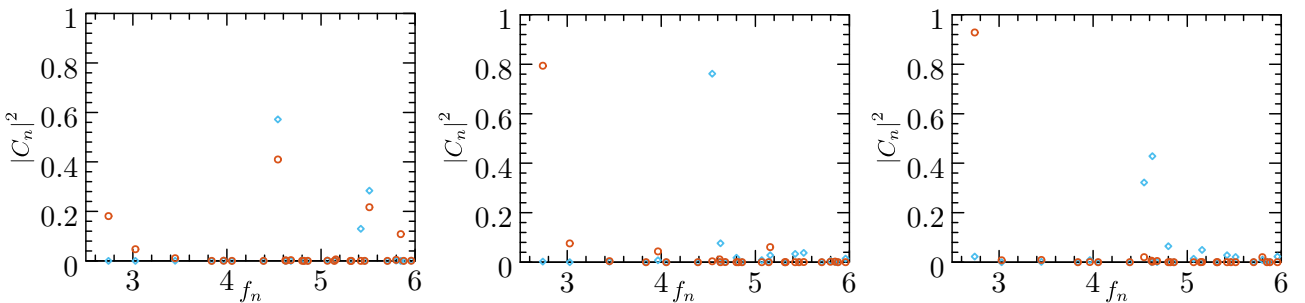


Figure 10 – Decomposition of the field numerically calculated by MoM (both electric (blue diamonds) and magnetic field (red circles) components, as shown in figure 7 and figure 8) onto the eigenmodes of a lossless rectangular cavity including the substrate of the PCB without the lines (see table 9).

investigated in the future.

4 Conclusion

Partly reverberating environments can increase or decrease the crosstalk between lines easily by several dB, which we have shown experimentally. This occurs once several modes of the cavity can be excited even if the

lines are placed close to the ground of the PCB. Additionally, the ensuing modification of the currents on them is not negligible. Thus the environment needs to be taken into account for the appropriate designs of PCBs to guarantee their functionality.

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