Analysis and Design of a Planar Antenna for a Millimetre-Wave Emitter using TLM

Klaus P. Heppenheimer, Larissa Vietzorreck, *Member, IEEE,* and Peter Russer, *Fellow, IEEE*

Institut für Hochfrequenztechnik, Technische Universität München
Arcisstr. 21, D-80333 Munich, Germany, eMail: vietzorreck@ei.tum.de

Abstract— **In this paper we investigate and design a planar patch antenna using the Transmission Line Matrix method (TLM). The planar antenna is part of a monolithic integrated millimeter-wave emitter, working in the 60 GHz range on a high resistivity silicon substrate. The active part will be realized by an negative impedance amplifier, here an IMPATT diode, the patch antenna is used as resonator as well as radiating element. For designing an appropriate resonator the design criteria are the desired frequency, an impedance match with the impedance of the IMPATT diode and the radiation characteristic and efficiency. For technological reasons a 525 μm substrate had to be chosen, which naturally will deteriorate not only the radiation features of the antenna, but also the behaviour of the impedance. The requirements concerning the impedance are a very low real part of the input impedance of the antenna ($\leq 3\ \Omega$), smaller than the negative impedance of the IMPATT diode in order to enable exponentially increasing oscillations. The imaginary part of the antenna has to show a steep gradient above the resonant frequency up to values $\geq 30, 40\ \Omega$. In order to find a design which will fulfill those critical requirements, a full wave analysis is demanded. The TLM method has proven to be a very powerful and flexible numerical method for the analysis of various planar and three-dimensional topologies, especially useful for the investigation of broadband structures, but yet has not been utilized extensivly for the analysis of radiating structures. It will be shown, how TLM can be used for antenna modeling, the necessary steps for the design of the patch antenna will be demonstrated and results will be validated by comparison with spectral domain methods.**

I. Introduction

In the next years there will be an increasing market for broadband millimetre-wave emitters to be used in communication and sensor applications. The availability of low-cost elements, easy to manufacture will play an important role. Monolithic integrated millimetre-wave emitters, realized on high-resistive silicon, can meet these requirements. Receiving and transmitting parts are integrated in the same element. Together with the high permittivity of the silicon substrate the miniaturization of the structure to a small and compact element is possible.

For the relevant frequency range around 60 GHz and due to the utilized substrate IMPATT diodes have to be considered as active element [1]. As radiating elements slot or dipole antennas have to be chosen according to the necessary suppression of the cross-polarization [2].

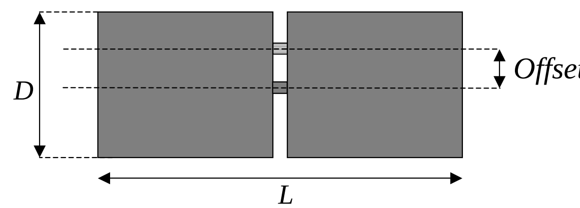

Fig. 1. Characteristic dimensions of the lambda/2-patch: length(L), width(D) and feeding point offset

In order to use the antenna as the resonator of the IMPATT oscillator two conditions must be fulfilled at the frequency of oscillation:

- The real part of the antenna impedance must be smaller than the magnitude of the (negative) real part of the impedance of the IMPATT diode.
- The imaginary parts of the impedances of the IMPATT diode and the antenna are of equal magnitude and opposite sign.

For technological reasons the substrate should not be thinned but keep its thickness of 525 μm, which will increase the real part of the impedance and deteriorate the radiation efficiency. Therefore measures have to be taken in order to improve the impedance and the radiation features of the antenna. For instance dielectric overlays of high permittivity or a structuring of the silicon substrate may be applied [3]. The

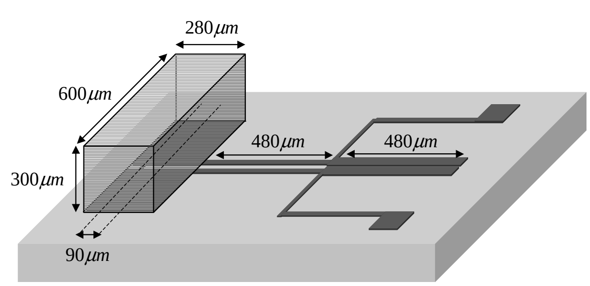

Fig. 2. Layout of the entire antenna with feeding circuit and dielectric overlay

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analysis of the resonator structure requires not only a very accurate tool, using a full wave analysis, to determine the very small and critical value of the input impedance. Moreover the possibility to consider three-dimensional dielectrics is needed as well as the presence of high-quality absorbing boundaries to model the free space. The calculation has to be performed in a broad frequency range and - as the structure should be optimized - with less numerical effort. Especially the last item is a demanding task as the difference in the geometrical dimensions between the small slots between the feed lines and the length of the resonator (see Fig. 2) has to be taken into account.

In this contribution the TLM method is proposed for the numerical characterization and design of the planar passive resonator [4], [5]. The time domain method gives accurate results by using less memory than frequency domain methods. Dielectric blocks or a structured substrate can be modelled without difficulties. The recently developed matched layers to truncate the computation domain allow to model the radiation of the antenna without great disturbances [6]. Due to the implemented parallelization, the in-house TLM program provides a fast and efficient tool for dealing with large computational domains.

II. Antenna modelling in TLM

In this section we shall give an overview concerning modeling details of TLM-simulated planar patch antennas.

A. Excitation

As we just want to determine the impedance of the passive resonator, we model the IMPATT diode by an ideal voltage source and excite the structure impressing an electric field on a conducting bridge between the patch wings by means of boundary field mapping. A broadband gaussian impulse – nearly Dirac – has been used for the excitation, as the resonator is completely linear.

B. Determination of the impedance

In order to evaluate the impedance, voltage and current at the feeding point have to be extracted from the simulation. These quantities may be defined using discrete line integrals. The values of the specified fields in single nodes of the TLM-mesh must be readout and summed up in every time step. Here we use centered field mapping to map between the internal network quantities and the field components. To avoid incorrect results for the voltage across the bridge, the voltage integral is placed on the metal at both ends.

C. Absorbing Boundary Conditions

The realization of absorbing boundary conditions represents the main difficulty in antenna modeling using TLM. Since locally matched walls are only useful for perpendicularly incident waves and other methods like PML or discrete greens functions are either quite complicate to implement or extremely inefficient, matched layers have been utilized. Test simulations have shown, that the choice of 5 matched layers in a distance of about one quarter (free space) wavelength (approximately 1000 μm) from the edges of the patch, performs a good compromise between accuracy and numerical efficiency. Neither an additional increase of the simulation area, nor a higher number of matched layers will have a significant influence on the calculated impedance.

D. Discretization

The problem of discretization has proven to be not remarkably serious. In the area of the patch a relatively rough discretization may be chosen without leading to lack of accuracy. For example, discretizing the slot between the patch wings (40 μm) with 4 nodes is fully sufficient.

E. Modeling of the Losses

Losses in high resistivity silicon substrates ($\rho \geq 10^4$ Ωcm) may be neglegcted in comparison to ohmic losses in the non-ideal metal [7]. A thin film resistor can easily be modeled using resistive impedance walls. The specific surface conductivity of gold is given to 2.2E7 S/m. Since the skin depth d_0 = 0,44 μm (60 GHz, gold) is less than the metallization thickness (1μm) and the surface conductivity of preferred alumina may be significantly lower than that of gold, a considerable deterioration needs to be taken into account. In most simulations the value for the metal conductivity is set to 2.2E6 S/m, which should guarantee a worst case estimation.

F. Near- to Farfield-Transformation

In order to obtain the radiation pattern of the antenna under investigation, a near- to farfield transformation can easily be performed by taking into account the field distribution on a surface surrounding the antenna.

III. Validation

First of all, in order to validate the used numerical algorithm for the analysis of antennas, the input impedance of a similar antenna configuration with a center frequency of 76.5 GHz on a much thinner (125 μm) substrate, calculated by TLM, was compared to a spectral domain approach [2]. A good consistency between the two calculations could be observed as depicted in Fig. 3. In the shown frequency range, the deviation in the real part does not exceed 1 Ω, whereas the divergence in the imaginary part is less than 10 %.

IV. Antenna design

A. Optimization of the Impedance

In the following it will be demonstrated, how TLM can be used efficiently for design and optimization of the 3-D antenna structure. Fig. 4 shows the impedance of the patch antenna on the thick substrate. The location of the antenna feed affects the level of the impedance, hence the calculations were performed for different offsets of the feeding point from the center of the structure (see Fig. **??**). At 60 GHz especially the real part of the input impedance is much too high.

Among other structural variants in order to improve the matching as well as the radiation efficiency, a dielectric layer with a high permittivity (ε_r=40) was deposited on top of the antenna. As shown in Fig. 5 the resistance could be decreased, but not enhanced to a satisfying level.

Another approach was the deposition of a dielectric block (see Fig. 2) on top of the antenna. With this means a much better matching can be achieved (see Fig. 6). It turned out, that the optimum dimensions for the dielectric overlay are given by a block just covering the antenna patch and at least 300 μm high. Fig. 7 shows the influence of a variation of the blocks geometrical parameters on the impedance of a dipole with 90 μm offset.

In Fig. 8 the input impedance of the whole structure including the feed network is depicted. The difference to the case without feeding network is not significant. The gradient of the real part of the input impedance is more gentle now, facilitating the fulfillment of the oscillation condition.

B. Radiation efficiency

Fig. 9 shows the effect of different configurations, which have been investigated in order to improve the radiation efficiency of the structure. The best performance is achieved

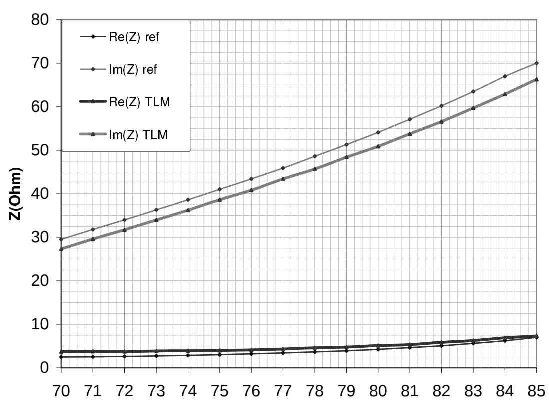

Fig. 3. Impedance of a patch antenna calculated with TLM compared to the results of a spectral domain method (ref) [2]

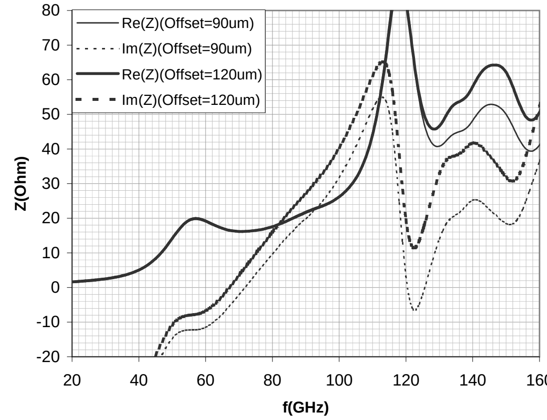

Fig. 4. Impedance of a 600 μm-dipole with 90 and 120 μm offset, resp., on a 525 μm - substrate

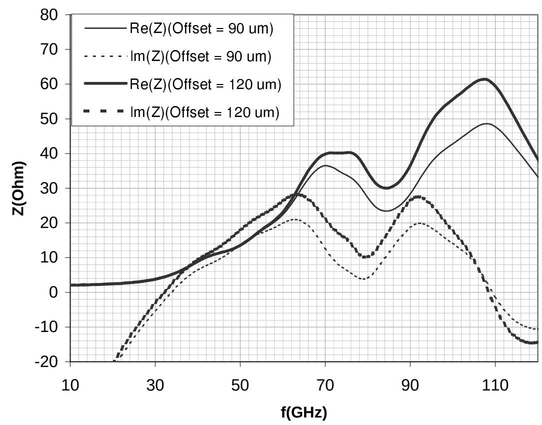

Fig. 5. Dipole with dielectric cover of high permittivity ε_r = 40. Impedance for a 600 μm · 280 μm - patch and 90 and 120 μm - offset, resp.

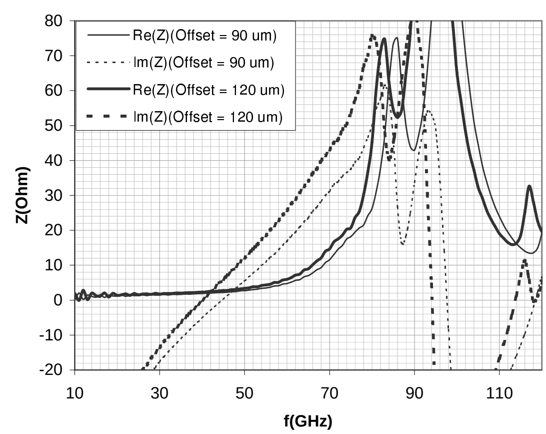

Fig. 6. Dipole impedance after deposition of a dielectric block (ε_r = 40) with geometrical values: height = 300 μm, length = 600 μm, width = 280 μm.

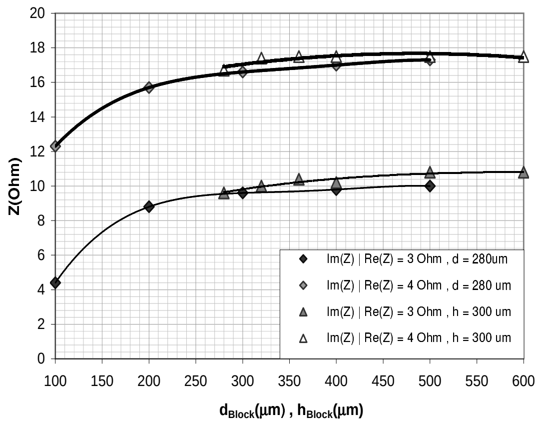

Fig. 7. Imaginary part of the dipole impedance under the constraint of invariance of the real part after deposition of a dielectric block as a function of the block parameters width and height.

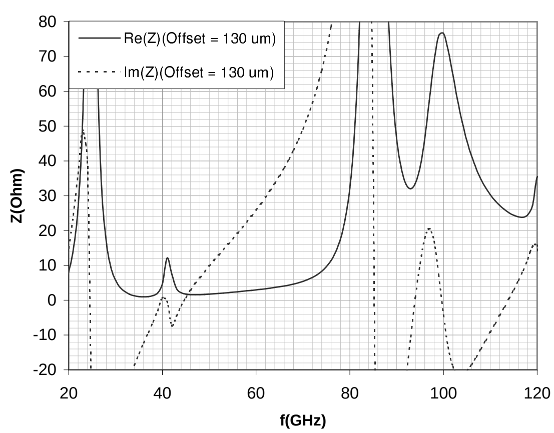

Fig. 8. Impedance of the dipole according to Fig. [1], with maximum offset of 130 μm

by the dielectric block on top of the structure in combination with an additional external perforation of the substrate outside of the antenna metallization, denoted by the variation of an effective ε_{eff} of the perforated silicon. [3]

V. Conclusion

It was shown, how TLM can efficiently be used for the analysis of radiating structures. Even elements with critical geometries – patch size compared to geometry of the feeding network – can be investigated fast and accurately. The quality of the absorbing boundaries allows a severe reduction of the computational volume, the parallelization reduces the computation time drastically. Calculations with varying parameters were performed in order to optimize the input impedance of the antenna. It could be be demonstrated, that

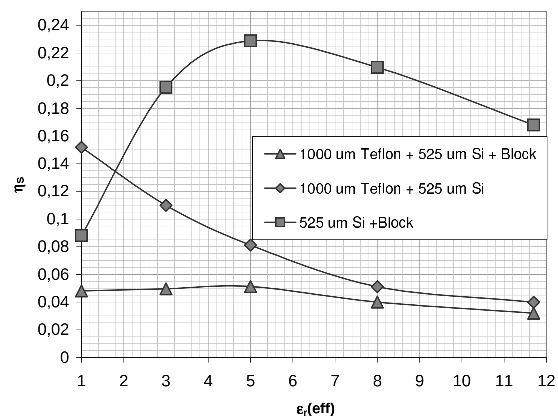

Fig. 9. Radiation efficiency of the dipole at 60 GHz for different configurations dependent on the effective permittivity, when the substrate is perforated in a region outside the antenna metallization.

the real part of the antenna impedance at the lambda/2 series resonant frequency of a planar dipole can be reduced considerably by positioning a dielectric block over the dipole. This will allow the use of thick substrates for self-oscillating active millimeterwave antennas. Otherwise the radiation efficiency could not be enhanced to an acceptable value. Here further steps like structuring of the substrate seem to be necessary.

Acknowledgment

The authors would like to thank T. Mangold for the implementation of the TLM code and many helpful discussions.

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