Electromagnetic modelling of GaAs membrane supported mm-wave receivers

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Abstract. This paper presents a new electromagnetic modelling approach for the design of GaAs membrane supported monolithically integrated mm-wave receivers. The receivers structures are divided into membrane supported sections and bulk GaAs supported sections. Each block is modelled and designed using the full-wave electromagnetic simulation software Zeland IE3D. The Schottky diode is included in the model using the internal port feature. The design steps include the Schottky diode experimental characterization, design and measurements of membrane supported antenna demonstrators and linear/nonlinear simulations of the final receiver structures. The fabrication processes is based on GaAs micromachining. Two types of video detection receivers were designed, fabricated and tested: a 38 GHz double folded slot antenna receivers and a 45 GHz Yagi-Uda antenna receiver. Both circuits monolithically integrated the antenna with the Schottky diode on the same 2.2 μm thin semi-insulating GaAs membrane. The experimental results demonstrate an isotropic voltage sensitivity of 3000 mV/mW at 38 GHz and 6000 mV/mW at 45 GHz, respectively. The measurements validate the modelling approach and open a window of opportunity for the development of innovative RF MEMS architectures operating at higher frequency, up to the sub-millimetre wave frequency range.

1. Introduction

The use of micromachining techniques has as its main effect the substantial reduction of losses in the millimetre wave range due to the substrate removal. Additional beneficial effects are the reduction of dispersion effects, the suppression of higher substrate modes and the possibility of using higher transmission line characteristic impedance values in the design. These improvements are due mainly to the fact that a very thin dielectric or high resistivity semiconductor membrane is used as support for passive circuit elements that appear as being “air suspended”.

In recent years, the micromachining technology has been proposed for the fabrication of millimetre wave circuits on very thin dielectric membranes, mostly for silicon substrates [1, 2]. Micromachining of GaAs is an exciting less explored alternative for manufacturing of components and modules for high performance communication systems. GaAs micromachining is very interesting for the RF-MEMS field also due to the easy monolithically integration of micromachined passive circuit elements with active devices manufactured on the same chip. The monolithically integration of a membrane-
supported antenna with a detecting Schottky diode is a practical solution for building very compact and low-cost receivers for the millimetre and sub-millimetre wave frequency range.

One possibility to build a receiving front-end is to use the direct conversion (video detection) technique. This approach has the following advantages: reduced complexity (no low noise local oscillator, complex microwave filters or amplifiers needed); low cost (important for mass production low cost applications); high level of circuit integration (low weight, small size); filtering only at low (video) frequencies.

This paper presents a new electromagnetic modelling approach for the design of GaAs membrane supported monolithically integrated mm-wave receivers. First section describes the electromagnetic modelling and the main steps of the design approach. Next the receiver structures fabrication is explained. After that, the design of two types of video detection receivers is presented: a 38 GHz double folded slot antenna receivers and a 45 GHz Yagi-Uda antenna receiver. Finally, the receiver structures characterization techniques and main experimental results are presented.

2. Electromagnetic modelling and design approach

The design approach of the receiver front-end splits the circuit into the membrane supported circuit block (micromachined antenna monolithically integrated with the mm-wave Schottky diode) and the bulk GaAs supported circuit block (low-pass filter for video output). Each block is modelled and designed using the full-wave electromagnetic (EM) simulation software Zeland IE3D [3].

This software package is a full wave, Method-of-Moments simulator and performs electromagnetic analysis for arbitrary 3-D planar geometry. The IE3D software package is based on open boundary Green’s functions formulation. This approach is well-matched for the modelling of antenna structures without metallic enclosures. The IE3D software includes an optimization engine that allows the using of multiple objective functions like return losses and antenna gain/directivity. The optimization variables are the main layout dimensions. The EM simulation results are saved in Touchstone type files and the whole circuit is analyzed and optimized using commercial nonlinear circuit simulation software based on harmonic balance method.

The design process involves few steps. First, test Schottky diode structures were designed and fabricated with the same technology used for the integrated receiver. A photo of the test diode structure is presented in figure 1. The diode is characterized using both DC and microwave reflection coefficient measurements. In order to increase the accuracy of the model parameter extraction, the diode was biased at several levels of the DC current and the measurements were performed in a large frequency range. The feeding coplanar waveguide (CPW) transmission line was modelled by means of EM simulations and for the Schottky diode the SPICE model was used. The extracted model parameters values were: saturation current $I_s = 10^{-13}…10^{-12}$ A; ideality factor $n = 1.24…1.27$; series resistance $R_s = 20…30$ Ω; zero-voltage junction capacitance $C_{jo} = 10…20$ fF; junction potential $V_j = 0.7…0.85$ V. An example of comparison between measured and simulated data, for two bias current levels, in the 10…65 GHz frequency range, is presented in figure 2.

Next, the membrane-supported antenna demonstrators were designed and measured [4]. The design starts with the analytical estimation of the antenna most important layout dimensions at the central operating frequency. Because the structures look being “air suspended”, these dimensions are usually expressed in term of free-space wavelength. Next the antenna performances are optimized for radiation pattern, antenna gain and return loss using intensive EM simulations. After the demonstrators manufacturing, they are characterized using “on wafer” reflection losses microwave measurements. The good agreement between EM simulated and experimental results reported in [4] validates this membrane supported antennas EM modelling approach.

The last step for the integrated receivers design is the EM optimization of the membrane supported antenna structure integrated with the Schottky diode and the bulk GaAs supported circuit block. In the EM model of the integrated receiver, the Schottky diode is included using the internal port facility of the IE3D software. For detector type receivers, the Schottky diode can be modelled by its small signal
bias dependent complex impedance. In this case it is possible to use the optimization engine of IE3D to design the receiver layout with matching between diode and antenna as objective function.

In order to verify the final layout design, a second dummy antenna (a dipole antenna) is placed in the far field of the receiver antenna and an EM simulation of the whole structure is performed for a large frequency bandwidth. The nonlinear diode model is connected at the internal port of antenna and the voltage sensitivity of the entire receiver structure is simulated.

Figure 1. The photo of a test Schottky diode structure

Figure 2. Measured and simulated reflection coefficient of the test Schottky diode structure

3. Receiver structures fabrication

Conventional and low temperature III-V MBE growth was used to fabricate the GaAs/AlGaAs/GaAs heterostructure [5]. Semi-insulating GaAs wafers ($\rho = 10^{7} \, \Omega \cdot cm$), with a thickness of 460 $\mu$m, were used as substrate. The MBE process started with a very thin (50 nm) buffer GaAs layer deposition. Over this layer, a 0.2 $\mu$m thin Al$_x$Ga$_{1-x}$As etch stop layer (with $x=0.6$) was deposited. Over the AlGaAs layer, a low temperature (LT) semi-insulating 2 $\mu$m thin GaAs layer ($\rho > 10^{6} \, \Omega \cdot cm$) was deposited. Following, two layers - 0.5 $\mu$m thick GaAs n type with $10^{18}$ cm$^{-3}$ doping and 0.5 $\mu$m thick GaAs n-type with $10^{17}$ cm$^{-3}$ doping were grown. The last two layers are necessary for the Schottky diode formation.

First the two mesas were formed. The first mesa, used for Schottky contact, was a 10x10 $\mu$m$^2$ square on the n layer. The second mesa (36x36 $\mu$m$^2$) surrounds the first one and reached the n$^+$ layer to facilitate the ohmic contact formation. For fabrication of the both mesas the dry etching process (RIE) with 0.6 $\mu$m etched depth was used. Rapid thermally annealed ([Au/Ge]x4/Ni/Au - with a total thickness of 0.2 $\mu$m) metallization formed the ohmic on the second mesa. The ohmic metallization was thickened up to 1 $\mu$m. The Schottky contact was fabricated on the first mesa using the Ti/Pt/Au metallization system.

The receiver metallization layout was defined using lift-off techniques. Before the last mask (backside-alignment for membrane formation) the wafer was lapped down to 150 $\mu$m. Selective RIE process with CCl$_4$F$_2$ and end point and optical detection were used for the formation of the membrane.

4. Double folded slot antenna receiver

The EM model of the membrane supported receiver module is presented in figure 3. The main block of the receiver is the double folded slot antenna monolithically integrated with the millimetre-wave Schottky diode. The membrane-supported antenna operates like in free-space. The distance between
the two folded slots as well as the length of one folded slot antenna were chosen to be approximately half the free-space wavelength at 38 GHz for the first step of the antenna design. Because the effective permittivity of the central CPW line is close to 1, there is no need to fold this line to assure the correct feed phase of the two antennas. The symmetry of the layout results in no need for air bridges to equalize the ground planes and the fabrication process is simplified. At the internal port of the receiver module the Schottky diode is connected. The differential port link the structure to the bulk GaAs module. This module consists of a low-Z/high-Z low pass CPW filter [6].

The receiver layout dimensions were optimized for maximum antenna gain and good matching between the diode and the antenna. The optimization variables were the distance between the two folded slots, the folded slot length, the DC return stub length and the dimensions of the central CPW line. The simulated 3D radiation pattern of the double folded slot antenna receiver at 38 GHz is presented in figure 4. The radiation pattern is bi-directional and almost symmetric, with a directivity of about 7.5 dBi in each direction normal to the circuit surface.

Figure 3. The EM model of the membrane supported double folded slot antenna receiver

Figure 4. The simulated 3D radiation pattern of the double folded slot antenna at 38 GHz

5. Yagi-Uda antenna receiver

The receiver layout used for electromagnetic simulation and design is presented in figure 5. The EM model of the receiver contains a membrane-supported Yagi-Uda antenna with 2 directors (with a gain of about 7...8 dBi). The antenna gain can be increased by adding more directors. At the feeding point of the Yagi-Uda antenna the Schottky diode is connected. The diode is monolithically integrated with the antenna on the same membrane using the fabrication process described in section 3.

A low-pass and matching network connect the diode with the video output port. Because the structure operates like in free space, the antenna design started from a scaled version of a classic Yagi-Uda antenna presented in literature for the UHF frequency range [7]. During the design and optimization of the receiver layout, the main goals were: diode matching (the bias dependent small signal diode equivalent is used) and maximum antenna gain at 45 GHz central operating frequency.

The optimization variables were the distance between the antenna elements and the dimensions of the low-pass and matching network. The simulated 3D radiation pattern of the Yagi-Uda antenna receiver at 45 GHz is presented in figure 6. The pattern has an end-fire radiation characteristic with a gain of about 8.2 dBi in the main radiation direction (parallel with the circuit surface).
6. Measurements and conclusions

The experimental setup used for the double folded slot antenna receiver characterization uses a horn antenna connected to a HP 83640A frequency synthesizer to illuminate the receiver structure. The horn antenna was placed in far field conditions and generated a plane wave propagating perpendicular to the receiver surface. The millimetre wave signal source was modulated in amplitude with a low frequency signal and the detected waveform was displayed using a digital oscilloscope.

Since the structure combines the function of an antenna and a detector, the “isotropic voltage sensitivity” $\beta_{V,iso}$ parameter was used to characterize the circuit performance [6]. The $\beta_{V,iso}$ is defined as the ratio between the amplitude of the output detected voltage and the incident isotropic power $P_{iso}$. The following formula is used to determine the isotropic power at the antenna plane:

$$P_{iso} = P_{gen} \cdot G_{HORN} \left( \frac{\lambda}{4 \pi R} \right)^2$$

where: $\lambda$ is the free-space wavelength; $R$ is the distance between horn antenna and double folded slot antenna; $G_{HORN}$ is the gain of the horn antenna and $P_{gen}$ is the power level at the output of the cables connecting the horn antenna and the signal source.

Figure 7 shows the isotropic voltage sensitivity as a function of frequency for a bias current of 10 $\mu$A. Considering the EM simulated antenna directivity from figure 4, these results are competitive with those reported in literature.

The experimental characterization of the Yagi-Uda antenna receiver was performed using an “on wafer” measuring set-up similar with those presented in [8]. A full characterized micromachined Yagi-Uda antenna was placed in the same plane with the receiver structure in far field conditions. The antenna was connected to an amplitude modulated mm-wave signal generator and operated as an emitter. The receiver structure collects the signal and detects the low frequency component that is amplified by a low-noise amplifier and then displayed using a digital oscilloscope. The input isotropic power was calculated with (1) and the experimental results for isotropic voltage sensitivity at a bias current of 50 $\mu$A are presented in figure 8.

The larger value for the isotropic voltage sensitivity measured for the Yagi-Uda antenna receiver in comparison with that obtained for the previous receiver can be explained by the loss of about 3 dB in the antenna gain because the bi-directional radiation pattern of the double folded antenna.
The good experimental results validate the EM modelling approach for the membrane supported mm-wave receivers that was presented in this paper. In the same time, they demonstrate that the monolithically integration of antennas and active devices on the same semi-insulating GaAs membrane opens a window of opportunity for the development of innovative architectures for circuits and systems operating at higher frequency, up to the sub-millimetre wave frequency range.

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