Numerical and Experimental Analysis of Nonradiative Dielectric Guide Modulator and Mixer at Ka Band

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***Abstract*—This letter describes the numerical analysis of an on/off modulator and a single-ended mixer in nonradiative dielectric (NRD) guide configuration at Ka band. Currently, only experimental results are available for such structures. A shunt mounted diode switch in NRD guide configuration is analyzed using the finite element method (FEM) in conjunction with linear circuit simulation. A novel mixer is similarly analyzed using FEM and harmonic balance analysis. The results obtained from numerical analysis are compared with measured results. It is demonstrated that some counter-intuitive experimental results can be explained through numerical analysis.**

***Index Terms*—Finite element method (FEM), hybrid system analysis techniques, mixer, nonradiative dielectric (NRD) guide, on-off modulator, Schottky barrier diode.**

I. NRD GUIDE CIRCUIT

FIG. 1 shows the geometry of the NRD guide, and the photograph of an on/off modulator in this guide. The theory, technique of shunt mounting the diode and applying dc bias, to get a modulator (or switch), is the same as that reported in the literature [1], [2]. In the present structure, a GaAs flip-chip Schottky barrier diode (SBD)—Alpha Industries part number DMK2790—is used as the switching element. This circuit can be used as a single-ended mixer in addition to a modulator. In Fig. 2, the mixer configuration is shown with the two waveguide ports being used as R.F. and L.O. For use as modulator, no change is required in the circuit. The switching signal can straightaway be applied to the d.c. bias terminal, and the waveguide ports are now used as input and output. The IF port becomes redundant in the modulator.

II. ANALYSIS AND MEASUREMENT OF MODULATOR

The dominant electric field of the LSM_{01} mode in the NRD guide is parallel to the diode. So the modulator is expected to reflect when the diode is biased ON and pass the signal when the bias is reversed or removed. The observed behavior is just the opposite, and this is also reported in [1]. Numerical analysis of this structure gives the explanation.

Agilent HFSS 5.5 software, which uses the finite element method (FEM), is used to analyze the modulator *as a multiport structure as seen from the diode terminals*. The information obtained is then used to complete the circuit analysis including diode in Agilent ADS2003A software. The important

Manuscript received February 19, 2004; revised March 11, 2004.

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Digital Object Identifier 10.1109/LMWC.2004.829263

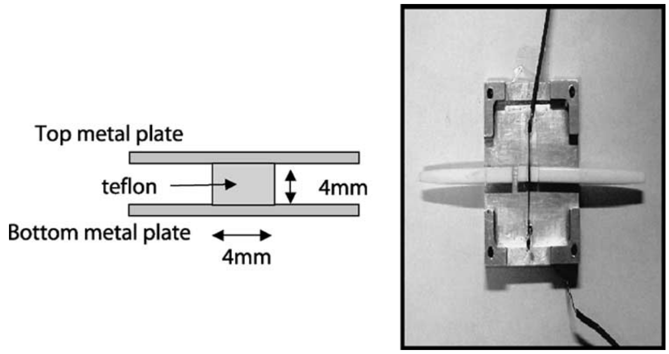

Fig. 1. NRD guide cross section and photograph of interior of modulator.

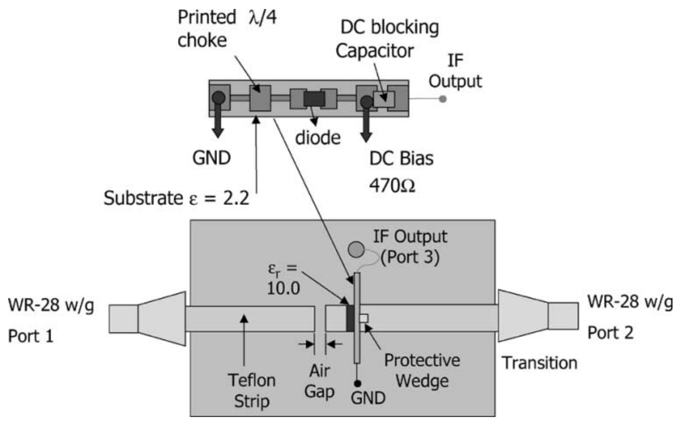

Fig. 2. Structure of the dual-purpose circuit in mixer configuration.

diode SPICE parameters [3] were $Rs = 4\ \Omega$, $Is = 0.5$ pA, $\mathrm{n} = 1.05$, $Cjo = 50$ fF, $Vj = 0.82$ V, $\mathrm{m} = 0.5$, and $\mathrm{tt} = 10\ ps$. However, it was very important to use the physical structure of the Schottky barrier diode (Fig. 3) in the simulation. Hereafter we refer to the actual active diode, having approximately 20 μm × 20 μm area, as "the diode," as separate from the metallized GaAs brick. The diode can now be treated as a true lumped element, even at 40 GHz. Boundaries which are open in the actual structure are simulated as metal boundaries for saving simulation time; since radiation is negligible in NRD guide, this does not introduce significant error. In the HFSS simulation, other than the input and output waveguide ports, an internal port is defined at the location of the diode. Details about the implementation of the internal port in HFSS can be found in [4]. Labeling this internal port as Port 3, we get a three-port structure which is simulated using HFSS and the three-port S-parameter data are then imported into the circuit simulator in the standard "Touchstone" format. In ADS, the diode is connected across Port 3, and a small-signal ac analysis

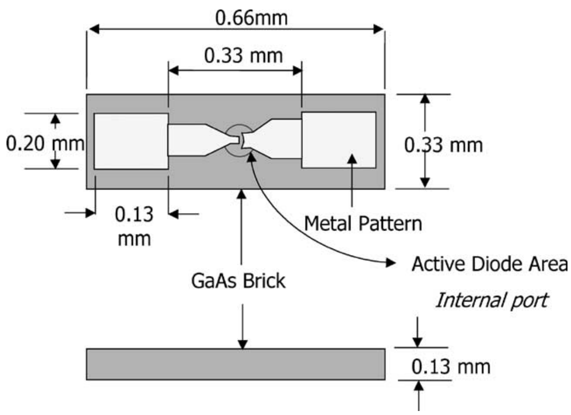

Fig. 3. Dimensions of the Schottky diode chip.

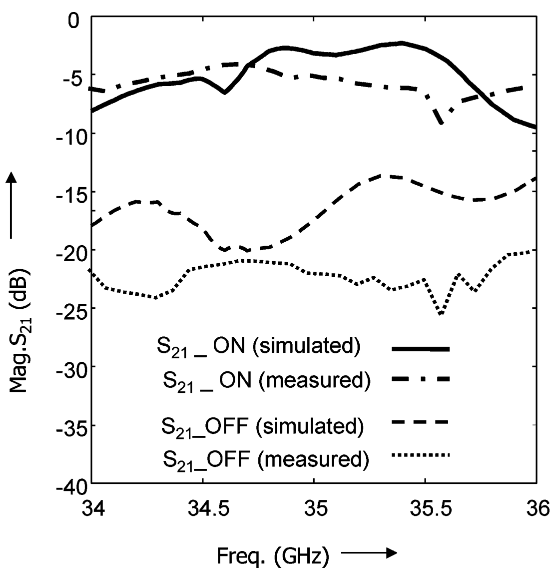

Fig. 4. Simulated and measured performance of modulator.

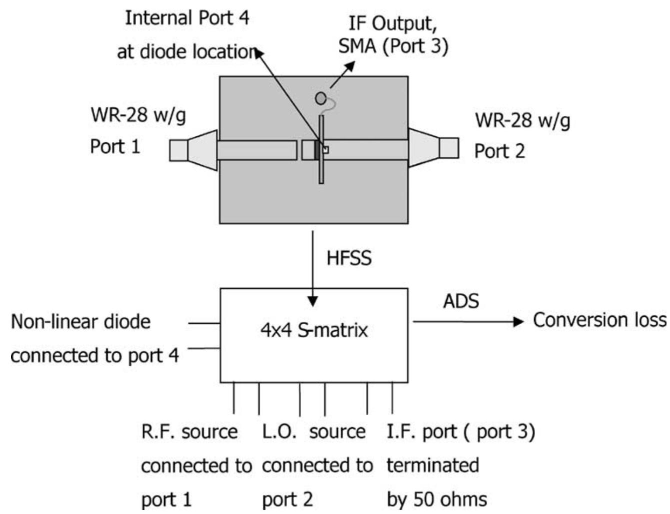

Fig. 5. Mixer simulation process.

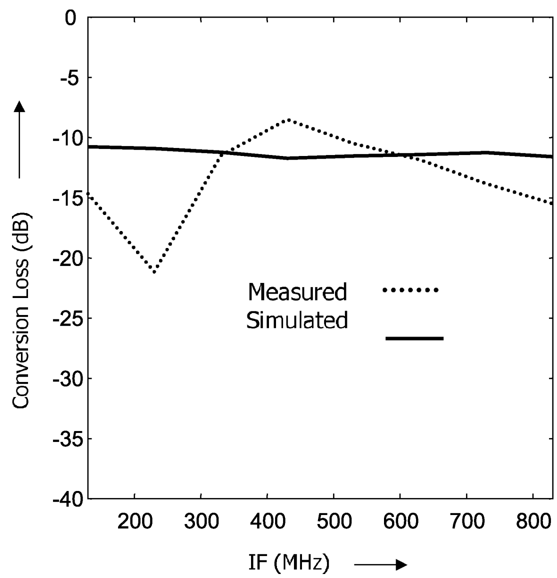

Fig. 6. Simulated and measured performance of mixer.

is carried out to obtain the two-port S-parameters of the modulator. The theoretical results are shown together with the experimental results in Fig. 4. The increased loss in the measured results can be reduced by better polished surfaces, finely aligned joints of Teflon strips, etc., but the present emphasis is not on this aspect. More analysis and experimentation (which will be reported elsewhere) has shown that this behavior is caused by the significant capacitance between the bonding pads through the GaAs brick, which appears in parallel with the inductance of the current path in the diode.

III. Analysis and Measurement of Mixer

This procedure is similar to the modulator analysis, except that the harmonic balance technique is employed for nonlinear analysis in ADS. The principal limitation of this type of analysis is that at Ka band (or higher) it is difficult to get meaningful results from the HFSS analysis at harmonics above the second, due to the large number of propagating modes at frequencies above 100 GHz for a structure designed for 35 GHz. For this reason, the number of harmonics was limited to 2. The simulation process is shown in Fig. 5, and the results are shown in Fig. 6. The conditions for measurement were: $\mathrm{L.O.\ power} = 5$ dBm, $\mathrm{L.O.\ frequency} = 34.8$ GHz, $\mathrm{R.F.\ power} = -18$ dBm, diode bias $\mathrm{current} = 2.8$ mA. The measurements were made on an HP8564EC spectrum analyzer, and were confirmed with a Rohde and Schwarz NRVS power meter. For reasons given above, the agreement is not very good, although the measurement shows that the mixer performance is quite satisfactory. This mixer configuration is not reported elsewhere, and is significantly simpler to fabricate compared to the balanced NRD mixer [1]. Like any single-ended mixer, it does not have the isolation and AM noise rejection of the balanced NRD guide mixer, but this is not an issue in any commonly used NRD guide system.

IV. Conclusion

The analysis of NRD guide on/off modulator and a novel mixer is carried out using ADS in combination with HFSS. Although incorporation of nonlinear devices into full-wave simulation is not new [6], the present approach, using commercial software to simulate practically useful millimeter-wave circuits has not been reported, to the best of our knowledge. The simulated response matches experimental results reasonably, for linear simulations. These results confirm that the function of the modulator incorporating a shunt diode switch cannot be explained simply by replacing diode by short and open circuits in its on and off states, respectively, as is normally done in shunt diode switches. A more accurate equivalent circuit of the diode taking into account the chip diode structure is required. For the mixer and other nonlinear circuits, a procedure for handling the multimode structure at harmonics has to be worked out.

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