Abstract—This paper presents a measurement-based analysis of operation of an example MOSFET detector integrated with a narrow-band patch antenna. First, responsivity of the detector was measured versus frequency of incident wave revealing two responsivity peaks, and then the antenna and the transistor were on-wafer probed to extract their impedances and antenna resonances in order to better explain the behavior of the detector.

I. INTRODUCTION

The MOSFET-based detecting structures reported often in the literature are aimed at detecting THz radiation in a broad frequency band. The authors rarely analyze the responsivity of their detectors as a function of frequency, and concentrate on maximizing this parameter by careful analysis of its sensitivity to gate bias [1]. However, with careful design of the antenna, the detector can be made responsive to pre-selected frequency bands, which opens possibilities of applying the MOSFET-based detecting technology in cheap spectrometry solutions or “multi-color” imaging.

This paper presents a measurement-based analysis of operation of an example MOSFET detector integrated with a narrow-band patch antenna operating in the frequency band centered close to 240 GHz. Such a detector was designed and subsequently realized utilizing multilayer commercial CMOS 400 nm technology. In order to facilitate analysis of the structure, additional components were also manufactured on the same sample/technology run. A plain patch antenna was manufactured with a transition from the co-planar waveguide to the microstrip line added to allow for direct measurements of its input impedance through on-wafer probing techniques in the frequency band of interest. Additionally, the chip also contains a stand-alone MOSFET device of the same dimensions like in the active element built into the detector.

The CMOS technology selected for this design makes it possible to use as many as 4 metallization layers. Only two were fully employed: the radiator as well as the microstrip (MS) feed line was realized on the top metal layer while the ground plane was designed on the bottom metal layer. The metal layers 2 and 3 were only employed to construct a transition between the ground tips of the Ground-Signal-Ground (GSG) co-planar (CPW) probes and the ground plane of the MS line (CPW-MS transition). By eliminating the internal metallization layers it was possible to create a continuous approx. 2.335-µm-thick layer of silicon dioxide (SiO₂) between the ground and the radiator acting as a relatively low-loss dielectric layer. A similar approach to patch antenna manufacturing was already reported in [2].

II. MEASUREMENTS

The responsivity of the complete detector was measured in a set-up consisting of a sub-THz source AMC10 from VDI, Inc, providing approx. 1 mW monochromatic incident wave of frequency that is selectable in the band of 200–350 GHz with a resolution much better than 1 GHz. The measurements were repeated several times using two different samples of the same chip with the same pattern of bias and signal wirebonds. The results were then averaged to minimize the effect of multiple reflections that typically introduce artificial minima and maxima into the responsivity curves.

As another step in detector characterization, the stand-alone patch antenna and the MOSFET realized on the sample next to the detector were probed using the Agilent’s PNA-X Vector Network Analyzer (VNA). Its measurement range was extended to 220–330 GHz using heads from the OML, Inc integrated with a pair of matching on-wafer probes from DMPI, Inc. The set of the heads consisted of a transmitter and a receiver (a Tx-Rx system).

Because the measurement was performed with the Tx-Rx system, applying typical full 2-port calibration techniques (e.g. Thru-Reflect-Line) was not possible. For this reason, in order to obtain measurements of the antenna structure and the transistor two additional CPW-MS transition elements (open and shorted) were designed and manufactured on the same chip. Based on the measured reflection coefficient of these two OPEN and SHORT standards, a numerical model of the CPW-MS transition was built and tuned to match the measurement characteristics. The model is based on the Method of Moments (MoM) where it is particularly easy to define CPW ports with three tips offset by specified pitch that can contact the pads of a planar structure at any location, just like with the real GSG probes. Prior to measurements the GSG probes were probe-tip calibrated using the dedicated set of calibration standards that include also the 50-Ohm Match standard. Thus, it can be safely assumed that the reference impedance of the measurement is known and can be used in the process of defining the CPW-MS transition model.

The CPW-MS transition model tuned against measurements was subsequently used to de-embed from measurements the [S]-matrices of the patch antenna and of the transistor. As a test, the model was first used to de-embed the measurements of the short and open, and the results are shown in Figure 1a. As shown, there is a noticeable phase shift between the results and the ideal open/short, which results from a 2.3-micrometer-long via to ground (SHORT), and stray capacitance at the open MS line (OPEN). The large spread of measurement points results from the characteristics of the heads.
Using the CPW-MS model it was possible to measure the transistor input impedance $Z_T$ (MOSFET’s G-S impedance) at the voltage $V_{GS}$ bias corresponding to the best responsivity obtained during the responsivity measurements. The voltage nearly closes the transistor channel (pinched-off), which agrees well with the literature [3]. Similarly, the antenna impedance $Z_A$ was also measured and de-embedded. Both impedance curves are shown in Figure 1a.

### III. RESULTS

With the impedances of the transistor and the antenna it was possible to use well-known formula to obtain the reflection coefficient:

$$\Gamma = \frac{Z_T - Z_A^*}{Z_T + Z_A}, \quad (1)$$

where $Z_A^*$ denotes complex conjugate of $Z_A$.

In Figure 1b, the amplitude of the obtained reflection coefficient is shown. Since, in general, the result depends on the choice of the reference plane, the calculations were performed at the transistor input plane. Two minima in the vicinity of 240 GHz are visible which may suggest a relatively good match at the interface in this band.

Responsivity of the detector was measured and is shown in Figure 2. As expected based on the reflection coefficient behavior, the responsivity peak is located at 240GHz or in the vicinity of the operating frequency of the patch antenna. However, the peak is narrower than the operating band defined by the impedance matching. Moreover, the measurements revealed another strong peak centered at the frequency of 270 GHz.

A partial explanation of this effect is introduction of a considerable number of slots in all large metallization planes due to technology requirements at the last stage of design process. The slots had a negative effect on the responsivity of the system reducing the radiation efficiency of the patch antenna. As a result, the registered photo-detection is weak, and it can be expected that the observed secondary peak may be a result of long biasing lines (or wire-bonds) subjected to the incident field. Nevertheless, the approach to the analysis of detectors presented in this communication is tempting and will be applied to other detectors.

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### IV. REFERENCES

