# Hybrid Electromagnetic Modeling of Lens-Integrated Antennas for Non-Contact On-Wafer Characterization of THz Devices and Integrated Circuits

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***Abstract*****─**A hybrid full-wave/quasi-optical electromagnetic model for the design of lens-integrated THz antennas for high frequency non-contact device characterization (30 GHz – 3 THz) is presented. Experimental validation of the antenna properties (input impedance and radiation pattern) is also provided to demonstrate the accuracy of the proposed model.

***Index Terms*** **─** Double-slot antenna, lens antenna, moment method, ray tracing, sub-millimeter waves.

## I. INTRODUCTION

Millimeter wave (mmW: 60-300 GHz) and sub-millimeter wave (sub-mmW: 300-3000 GHz) bands are poised to become increasingly utilized in many key applications in the near future, such as high-speed communications, sensing and imaging as well as spectroscopy and non-destructive evaluation. All-electronic systems that can achieve ultrafast switching and extremely-high-frequency operation are badly needed for the proliferation of such sensing and spectroscopy methodologies. In an effort to realize such systems, millimeter-wave and sub-millimeter-wave integrated circuit (IC) technologies using high electron mobility material systems and novel device topologies are being considered.

In addition, testing and characterization of such ICs at their intended operation frequency has long been a challenge due to several bottlenecks. Particularly, the physical fragility of fine-tip contact probes used for on-wafer characterization incurs high maintenance costs and are plagued by repeatability issues. These problems are exacerbated as the operation frequency approached 1 THz, leading to prohibitive costs and large measurement errors.

As an alternative, we recently developed [1] a non-contact on-wafer device characterization approach using a low-cost and wear/tear free setup. This novel contact-free measurement setup consists of planar on-chip receiving and transmitting antennas in a coplanar waveguide environment as illustrated in Fig. 1. An electrically-large, high-resistivity silicon hemispherical lens couples the signals into and out of the device-under-test through the on-chip antennas. To optimize antenna-to-device coupling over a wide bandwidth, the antenna design as well as the effects of the electrically-large, high-index material (n~3.5) lens need to be carefully modeled. Here, we present a hybrid electromagnetic model that employs the Moment Method (MoM) for the slot antenna on the focal plane of the lens and a Ray-Tracing/Huygens-Integral to capture the first-order effects of the electrically large lens. With this approach, a system level computational analysis of the non-contact probe setup can be evaluated. The overall signal coupling performance into and out of the device-under-test can be accurately evaluated using this hybrid computational tool. As verification, the on-wafer antenna impedance is measured using conventional contact-probes at 325-500 GHz and comparisons of the experimental data along with full-wave simulations using HFSS-v.15 and the proposed hybrid approach are provided.

## II. PLANAR WIDEBAND ANTENNAS FOR ON-WAFER NON-CONTACT MEASUREMENTS

For contact-free device measurements in mmW and THz bands, the device-under-test is fabricated in a coplanar waveguide (CPW) environment, as illustrated in Fig. 1. The input signal is injected through a planar antenna interfacing with the CPW and placed at the focal plane of a large hemispherical lens. The scattered signal is coupled to the network analyzer's receiver port through a second planar antenna symmetrically placed at the output port of the device. As such, this system

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incorporates quasi-optical wave propagation for efficient signal coupling from the network analyzer ports to the on-wafer device terminals. However, due to the very large electrical size of the quasi-optical components (e.g., lenses and mirrors with apertures >30λ), a full-wave numerical simulation of the system is not practical for design purposes. Below, we present a hybrid approach that combines a full-wave solution for the antenna on the wafer and a scalar diffraction approximation to evaluate the effects of the electrically-large lens for fast and accurate analysis of the quasi-optical non-contact link between the test ports and the on-chip device.

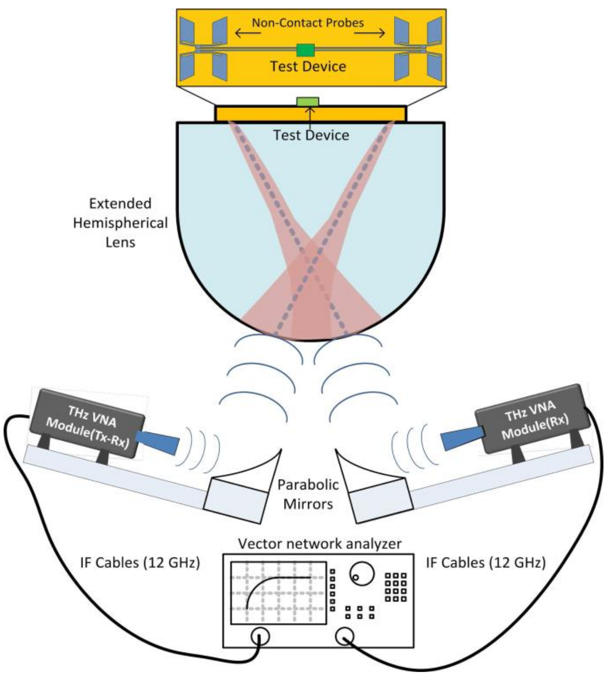



Fig. 1. Quasi-optical coupling setup for the non-contact probe testbed [1].

## III. HYBRID ELECTROMAGNETIC MODELING FOR THE QUASIOPTICAL SIGNAL COUPLING

Through careful design of antenna arms and the feed region, butterfly-shaped slot antennas, such as the design depicted in Fig. 1 can achieve much better impedance bandwidth than the previously-studied double-slot antennas [2, 3]. An important simplification can be realized for the antenna impedance design if we assume that the electrically-large hemispherical lens is infinite in extent. This assumption is justified since typical lens sizes are on the order of $d > 30\lambda$, where $d$ is the lens diameter. As such, the magnetic current distribution as well as the input impedance of the antenna can be computed using a half-space Green's function and the magnetic field integral equation (MFIE) [4].

This is achieved by incorporating the half-space Green's function to model the electrically large hemispherical lens, as discussed in [4]. Subsequently, the slot antenna placed at the lens-air boundary was analyzed using moment method in conjunction with quadrilateral elements and conformal rooftop basis functions as detailed in [5].

Curvilinear (bi-quadratic) quadrilateral finite elements and rooftop basis functions were used in the moment method implementation of the antenna problem, as illustrated in Fig. 2 (a) [5]. Although approximate, this approach is extremely efficient for antenna impedance design and to optimize the coupling between the antenna and the device CPW environment. Nevertheless, to evaluate the antenna far-field patterns outside the hemispherical lens and assess the overall signal coupling performance, a quasi-optical modeling of the probe antenna is still needed.

To a first-order approximation [4], the antenna magnetic currents computed via the MoM solution can be used to calculate the far-field radiation patterns into the lens dielectric (assuming an infinitely large lens). Subsequently, ray-tracing (or physical-optics) can be used to compute the antenna pattern outside of the hemispherical lens, as illustrated in Fig. 2 (b). To do so, we first compute the radiated fields just inside the lens-air interface. Next, we use the Fresnel transmission coefficients for both polarizations by tracing the rays emanating the antenna center and impinging upon the inner surface of the lens. Upon multiplying the radiated field intensities on the inner surface of the lens with the corresponding Fresnel transmission coefficients for each associated ray, the tangential electromagnetic fields on the outer surface of the lens can be computed. The final step to compute the antenna pattern outside the lens surface is to apply Huygens-Fresnel principle to the tangential field intensities on the outer lens surface. For example, Fig. 2 (c) depicts the computed E-field intensity of the probe antenna beams propagating away from the silicon lens. As seen, since the input and output antennas are located off the optical axis of the lens, the radiated/received patterns point away from the optical axis. As such, the input and output test signals can be effectively decoupled into the respective ports of the network analyzer using off-axis parabolic mirrors with minimal spill-over/cross-talk. The quasi-optical properties of the antennas beams, such as the Gaussicity [6] can then be calculated to optimize the overall probe system.

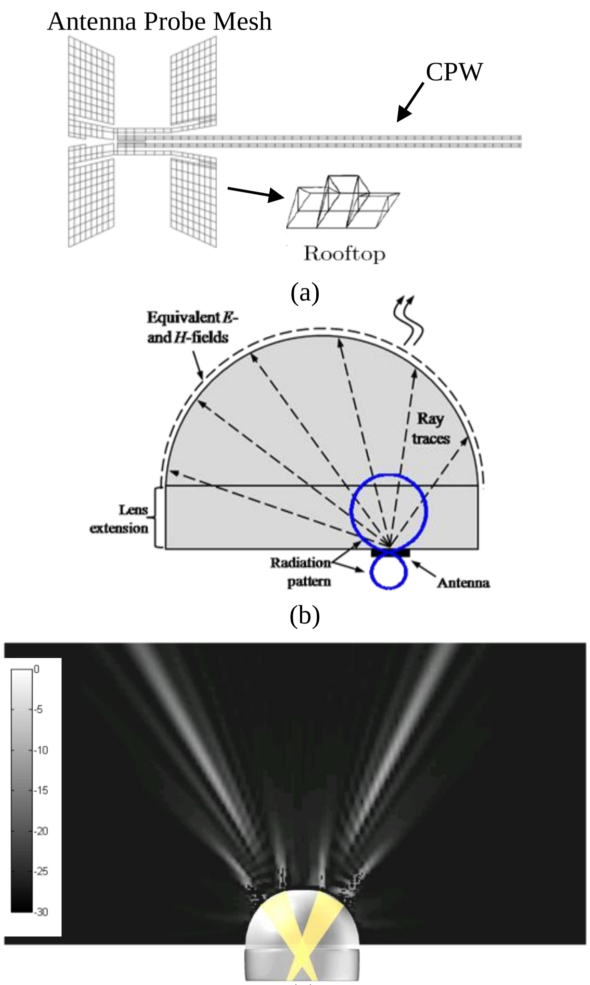



Fig. 2. Hybrid electromagnetic modeling of THz probe antennas: (a) discretization of the antenna slots with bi-quadratic mesh, (b) ray-tracing/physical optics analysis for the THz antenna radiation pattern in the presence of the hemispherical lens, and (c) computed *E*-field intensity distribution of both receiving and transmitting THz probe antennas.

## IV. EXPERIMENTAL VALIDATION OF NON-CONTACT PROBE ANTENNA DESIGN

To illustrate the effectiveness of the proposed approach, we fabricated and characterized a sub-mmW on-chip antenna at the WR 2.2 (325-500 GHz) band. A commercially available contact probe (i500 from Cascade Microtech) was used to conduct input impedance measurements while the antenna chip was placed over the metallic chuck of the probe station. The thickness of the antenna substrate was 380 µm (which is much larger than a quarter wavelength and thus satisfies infinite half-space assumption). However, the radiation boundary conditions are violated by the presence of the metal chuck. In order to mitigate this problem, a lossy silicon wafer (1 Ω.cm) with 500 µm thickness was added as an absorbing layer under the antenna substrate. In order to further isolate the chip under test from the chuck metal, a 3 cm thick Styrofoam was used as a supporting structure to the substrate and silicon slab. The illustration of this dielectric stack and the on-wafer micrograph of antenna-under-test are shown in Fig. 3 (a).

The contact probe was calibrated up to an on-wafer reference plane using the offset-short calibration kit shown in Fig. 3 (b). To do so, a Short-Open-Load (SOL)-type calibration [7] was employed to account for the systematic errors in the probing fixture, including the repeatable effects of landing pads, the CPW taper and the 100 µm-long section of the transmission line. Two additional standards were used to further suppress non-repeatable errors using a least-squares fit for the error matrix as discussed in [7].

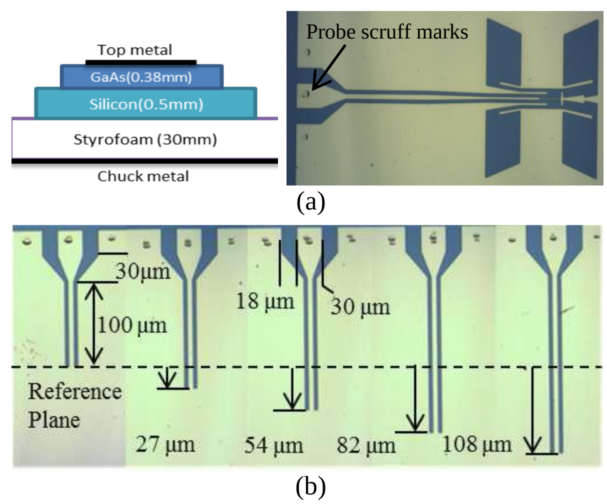
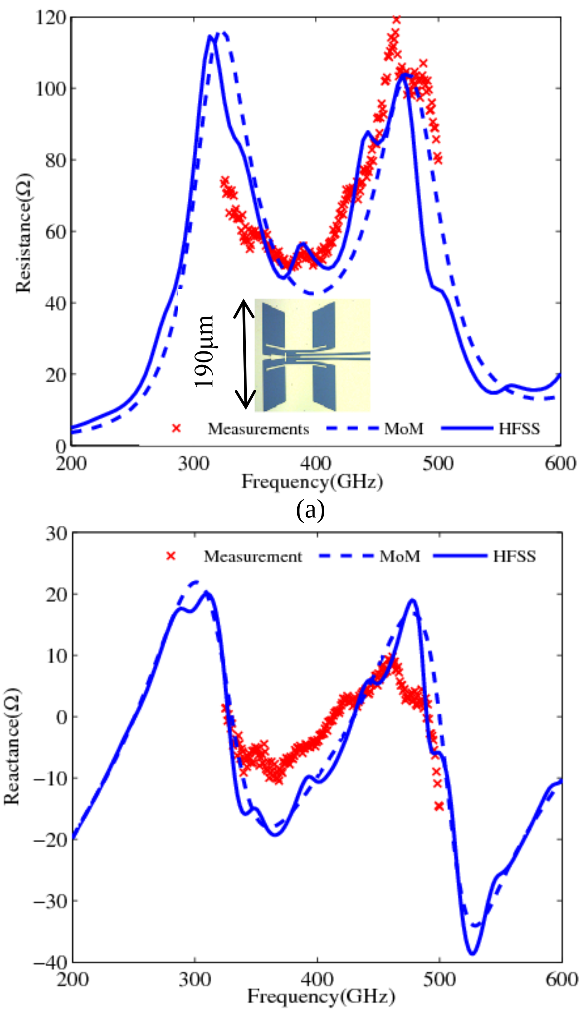



Fig. 3. On-wafer measurement of the non-contact probe antenna: (a) Illustration of the measurement layout and the micrograph of the fabricated antenna with contact probe landing pads, and (b) micrograph of on-wafer offset-short calibration kit

The measured input impedances of the two fabricated antennas are shown in Fig. 4, along with the MoM and HFSS-v.15 simulation data. As seen, both the real and imaginary parts of antenna impedance are in excellent agreement with both simulations. The slight deviations from computed antenna impedance are primarily due to variations in the micro-fabrication of the on-chip antennas. We note that the input impedance is very sensitive to the matching stub geometry at the center CPW connecting two slots to each other.

Design modifications implemented in the feed area do not significantly affect the radiation characteristics of the butterfly antenna, which is primarily determined by the shape of the slots. Radiation pattern measurements of this type butterfly-antenna topology can be found in [3].




(a)

(b)

Fig. 4. Antenna impedance: (a) resistance of the non-contact probe antenna (with micrograph of fabricated antenna on inset), and (b) reactance of the non-contact probe antenna

## V. CONCLUSION

We presented a hybrid electromagnetic modeling approach for accurate and efficient evaluation of non-contact probes for THz device characterization. The extremely-large computational cost of simulating the whole system has been significantly simplified by applying justified approximations. The proposed model brings together the principles from the RF/microwaves and optics regimes, and efficiently synergizes the two for modeling THz systems. This simple and accurate approach thus allows for a fast optimization of quasi-optical signal coupling from the network analyzer to the device under test.

## ACKNOWLEDGMENT

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