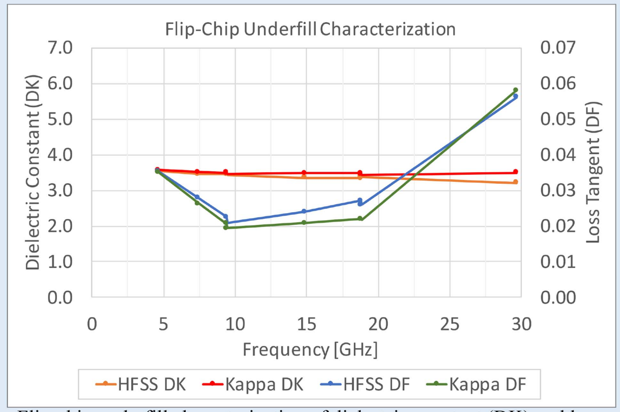
Dielectric and Underfill Characterization Using Cavity Resonators for Millimeter-Wave Applications

Robert B. Paul, *Member, IEEE*, A. Ege Engin, and Jerry Aguirre, *Senior Member, IEEE*

***Abstract*—Having an accurate dielectric constant and loss tangent when creating radiofrequency (RF) models in full-wave simulation is essential. With the introduction of new low-loss dielectrics and with the variability of dielectrics due to the manufacturing process, there is a need for a quick and simple method to characterize the permittivity of these materials. Dielectric characterization has become even more critical with the rollout of 5G cellular communications. At the higher frequency bands of 5G, around 28 GHz and 39 GHz, the dielectric losses can be significant, and the package design can be sensitive to dielectric constant variations. In this letter, two dielectrics are characterized; a flip-chip underfill material and a low-loss dielectric. Cavity resonators are used to extract the dielectric constant and loss tangent of flip-chip underfill, while substrate integrated waveguide (SIW) resonators are used to characterize packaging substrates. Simulations and extractions of the dielectric constant and loss tangent are completed at several frequencies using an in-house tool called Kappa Extractor, based on a rapid plane solver. The results are verified with a commercial full-wave simulator.**

***Index Terms*—Dielectrics, dielectric constant, dielectric losses, cavity resonators, flip-chip, loss tangent, underfill.**



Flip-chip underfill characterization of dielectric constant (DK) and loss tangent (DF) with a full-wave simulator (HFSS) and rapid plane solver (Kappa Extractor).

I. Introduction

DIELECTRIC characterization is important for accurate radiofrequency (RF) designs and modeling. The higher frequencies of 5G communications require characterizing new low-loss materials for use at millimeter-wave frequencies. In addition, there has been very little published on the RF characterization of underfill materials. The characterization of flip-chip underfill is vital for the reliability of chip on package.

Chip packages can support signals only up to the frequency where noise coupling (e.g., crosstalk, switching noise, etc.) starts causing malfunctioning of the system. Vertical interconnects such as vias and solder bumps are major sources of noise coupling and inserting ground references between every signal net is not practical. For the solder bumps, the noise coupling depends on the permittivity of the underfill material. Such liquid or semi-viscous materials are commonly characterized from a simple fringe capacitance model of an open-ended coaxial probe immersed in the material. This method, however, is not as accurate as resonator-based methods [1]. In [2], transmission/reflection measurements on a filled waveguide have been used. High-frequency properties of underfill materials are becoming increasingly important in 3D integrated circuits as underfill is typically needed between each stacked chip.

In this letter, an in-house rapid plane solver tool called Kappa Extractor is used to characterize dielectrics at microwave and millimeter-wave frequencies. Dielectric characterization in Kappa Extractor neglects any inductance or losses occurring in the walls along the height of the substrate

Take-Home Messages:

- Substrate integrated waveguide (SIW) resonators can be constructed on package with a via fence for the purposes of dielectric characterization.
- Cavity resonators can be constructed from dielectric filled copper cups, which are then plated, allowing for the characterization of flip-chip underfill.
- Constructed SIW resonators or cavity resonators along with the Kappa Extractor application can extract the complex permittivity much faster than using full-wave simulation.
- High accuracy dielectric characterization can be achieved for a variety of dielectric materials in a short amount of time.

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Robert B. Paul is with the Department of Electrical and Computer Engineering, San Diego State University, San Diego, CA 92182 USA (e-mail: rpaul@sdsu.edu).

A. Ege Engin is with the Electrical Engineering Department, San Diego State University, San Diego, CA 92182 USA (e-mail: aengin@sdsu.edu).

Jerry Aguirre is with Department of Research and Development, Semiconductor Components Group, Kyocera International Inc., San Diego, CA 92111 USA.

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integrated waveguide (SIW) resonator or cavity resonator, assuming perfect electric conductor is placed at the walls along the height. Here the height is very small in comparison to the width or length of the resonators and is therefore neglected in exchange for rapid solutions. Further, Kappa Extractor assumes a point source excitation at the ports, ignoring the diameter of the port pins. This allows the Kappa Extractor application to obtain a fast solution to the impedances at the ports as described in [3] and [4] using a rapid plane solver.

Dielectric characterization is accomplished by extracting the complex permittivity of a dielectric. This complex permittivity ε can be described using the permittivity of free space ε_0, dielectric constant ε_r, and loss tangent $tan(\delta)$, as represented in (1). The complex permittivity describes the way in which a dielectric polarizes when an electric field is introduced and the losses that are associated with this change in polarization.

$$\varepsilon = \varepsilon_r \varepsilon_0 (1 - j tan(\delta)) \quad (1)$$

In this letter, we use square cavity resonators, where the measurement ports are placed diagonally one-quarter of the length and width inwards from the sides of the resonators. The characterization of the dielectric constant (DK) and loss tangent (DF) is performed on both a semi-viscous material (flip-chip underfill) and a packaging material (Roger's RO4003).

Dielectric characterization is performed at the resonances of the cavities which can be calculated using (2) and is detailed in [5]. The dimensions of the cavity a, b, and d are the width, height, and length of the resonator, respectively. The number of half wavelengths across the width, height, and length are given as m, n, and l, respectively. In this case, n is zero because the height is much shorter than a half-wavelength at the frequencies measured here. The relative permeability μ_r is 1 in this case. The speed of light in free space is denoted as c and the dielectric constant is denoted as ε_r. The first three resonant peaks are used in this letter. These are transverse electric field modes TE_{101}, TE_{102} or TE_{201}, and TE_{202}.

$$f_{mnl} = \frac{c}{2\pi\sqrt{\mu_r \varepsilon_r}} \sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2 + \left(\frac{l\pi}{d}\right)^2} \quad (2)$$

The cavity resonators for the semi-viscous flip-chip underfill material are created as described in [6] using a solid-walled cup and then plating the top of the cup. The cavity resonator created in [6] was constructed with strips of copper fastened around the perimeter of the cup whereas this time the cup is milled out of a solid block of copper. Milling the cup means that there will be a 5 mil corner radius in the four vertical edges of the cavity resonator. Through full-wave simulations, it was determined that the 5 mil corner radius has very little effect on the extracted results. Furthermore, this 5 mil corner radius is accounted for when extracting the complex permittivity in full-wave simulation, but not in Kappa Extractor.

The SIW resonators that are fabricated on the Roger's packaging material are created using a via fence, which is effectively the walls of the cavities. There are three layers to the package: a core layer, a bondply layer, and another core layer. These cavity resonators offer a homogeneous resonating structure where the energy is contained within the cavity.

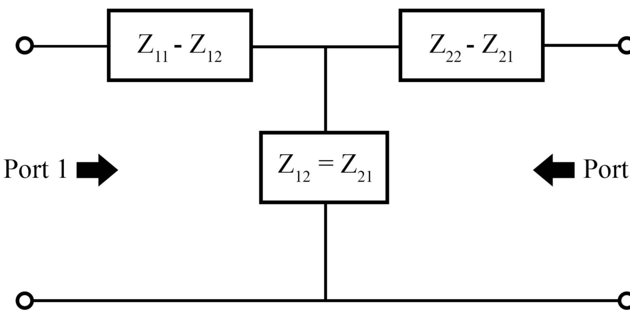

Fig. 1. T-equivalent circuit for a reciprocal two-port network.

The transfer impedance, Z_{12} or Z_{21} parameter, is used to characterize and extract the complex permittivity because it does not include any parasitic probe inductances seen at the ports. With reciprocal two-port networks, we can model the network as a T-equivalent circuit, as displayed in Fig. 1, and is explained in detail in [5], [7].

II. Simulation Setup

Kappa Extractor can extract the dielectric constant, loss tangent, cavity height, and surface roughness of the SIW resonator or dielectric-filled cavity resonator [8]. All of the simulations performed in this letter with Kappa Extractor optimize dielectric constant, loss tangent, and cavity height in order to fit simulation with measurement. The number of mesh cells across the width and length of each resonator simulated in Kappa Extractor is 64 by 64 cells, respectively.

Alternatively, these same dielectrics are characterized using a full-wave simulator (HFSS) by modeling a geometry as close to the actual structures as possible. The extraction of the complex permittivity is achieved by iteratively performing simulations while varying the parameters and overlaying the plot on top of measurement to get the best fit visually.

In full-wave simulation, finite conductivity boundary conditions are placed on the faces of the conductors. Waveports are used in full-wave simulation to excite the signal pins of the resonators. The same conductivity values and roughness models are used in both full-wave simulation and Kappa Extractor. A conductivity of $5.8 \times 10^7 S/m$ is used for copper and the Groiss roughness model is used.

III. Flip-Chip Underfill Characterization

A. Design of the Cavity Resonators

A series of underfill filled cavity resonators were fabricated on one solid copper block. These cavity resonators have dominant mode resonances (TE_{101}) at 4.70 GHz, 9.44 GHz, 18.84 GHz, 37.34 GHz, 46.03 GHz, and 60.59 GHz. Stainless steel pins are pressed into pre-drilled holes in the base of the cavities. The cavities are filled with the underfill material and cured in a furnace, the excess underfill on top is lapped, the top is sputtered with platinum, the top is electrolessly copper plated, and the port pins are milled for a clearance around

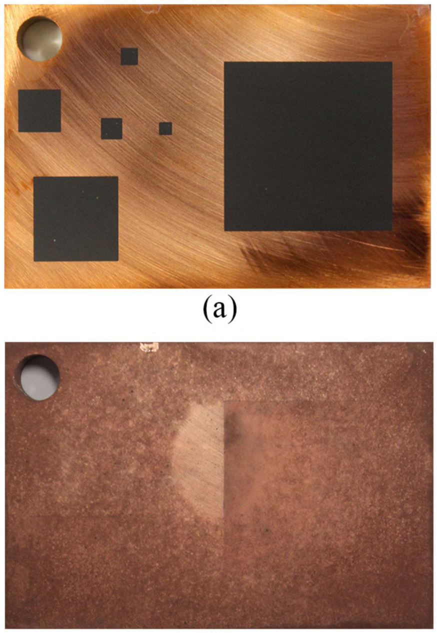

Fig. 2. Underfill cavities (a) filled and cured with underfill, then lapped; and (b) plated with electroless copper plating.

them for probing. The construction of the set of cavities is shown in Fig. 2.

B. Measurement of Flip-Chip Underfill

The cavities were measured on a vector network analyzer (VNA). Both ground-signal-ground (GSG) coplanar microprobes and ground-signal (GS) microprobes were used to measure the impedance parameters of the package. The GS probes were used to measure the three larger cavities, and the GSG probes were used to measure the three smaller cavities. Short-open-load-thru (SOLT) calibration was performed prior to measurement. Measurements were performed up to 67 GHz, but only the three largest cavities were used for extracting the permittivity.

C. Extraction Result of Flip-Chip Underfill

Using both full-wave simulation and Kappa Extractor, the dielectric constant and loss tangent were extracted. The plots in Fig. 3 and Fig. 4 show the first resonance of each cavity resonator. This is the dominant mode resonance TE_{101}, where there is one-half wavelength in both the x and z directions (width and length) of the cavity resonator. The y-direction (height) is much shorter than the x and z directions and is a small fraction of a wavelength. Therefore, there is no standing wave resonance in the y-direction.

Extractions at the first three standing wave resonances were performed on each of the cavity resonators. These are resonant modes TE_{101}, TE_{102} or TE_{201}, and TE_{202}.

In Fig. 3 and Fig. 4, good alignment is seen between measurement and simulation using both Kappa Extractor and the full-wave simulator. In Kappa Extractor the dielectric constant, loss tangent, and cavity height are all optimized to align the simulation with measurement.

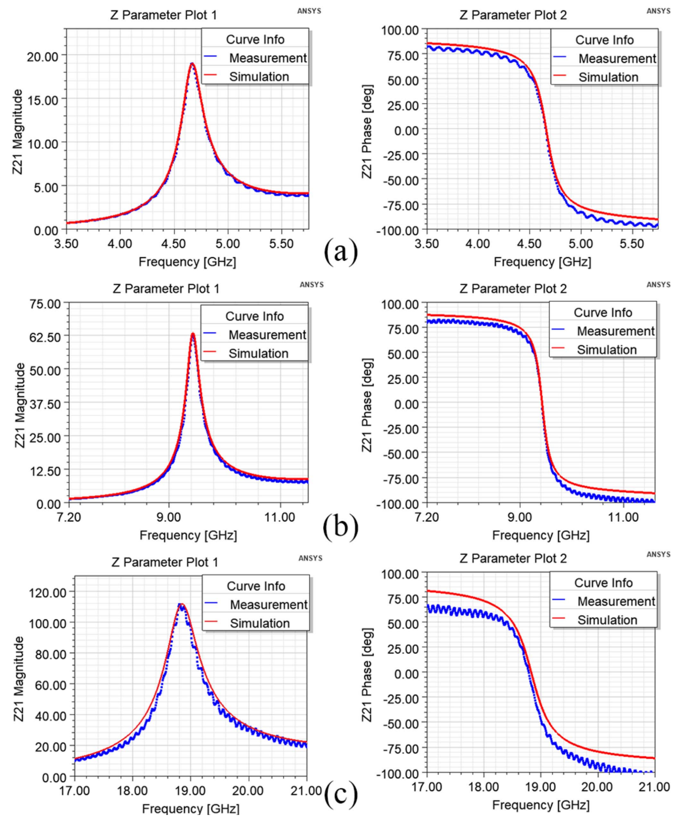

Fig. 3. Overlay of measurement and simulation of flip-chip underfill using full-wave simulation. Transverse electric field mode TE_{101} magnitude and phase of (a) resonator 1 at 4.70 GHz, (b) resonator 2 at 9.44 GHz, and (c) resonator 3 at 18.84 GHz.

A comparison of the results from full-wave simulation and Kappa Extractor are shown in Table I. It is important to note that the cavity height used in Kappa Extractor and full-wave simulator are different and contribute to the deviation seen between the results of the two different solvers. The cavity height is adjusted in Kappa Extractor to better fit simulation with measurement, while the nominal cavity height is used in full-wave simulation. Cross-sections of the cavities were not taken to verify the actual heights of the cavities. Another source of error in Kappa Extractor is due to the simplifications made by the rapid plane solver, assuming that perfect electric conductor is placed at the walls of the cavity resonator. Lastly, the 5 mil corner radius in the cavities due to end milling was accounted for in full-wave simulation but not in Kappa Extractor.

As shown in Table I, the dielectric constant extracted using Kappa Extractor is within 9% of what was extracted with full-wave simulation up to 30 GHz. The loss tangent extracted using Kappa Extractor is within 20% of what was extracted using full-wave simulation up to 30 GHz.

IV. Roger's Material Characterization

A. RO4003 Board Design and Stack-Up

The Rogers RO4003 material has a nominal dielectric constant of 3.55 and a nominal loss tangent of 0.0027. The

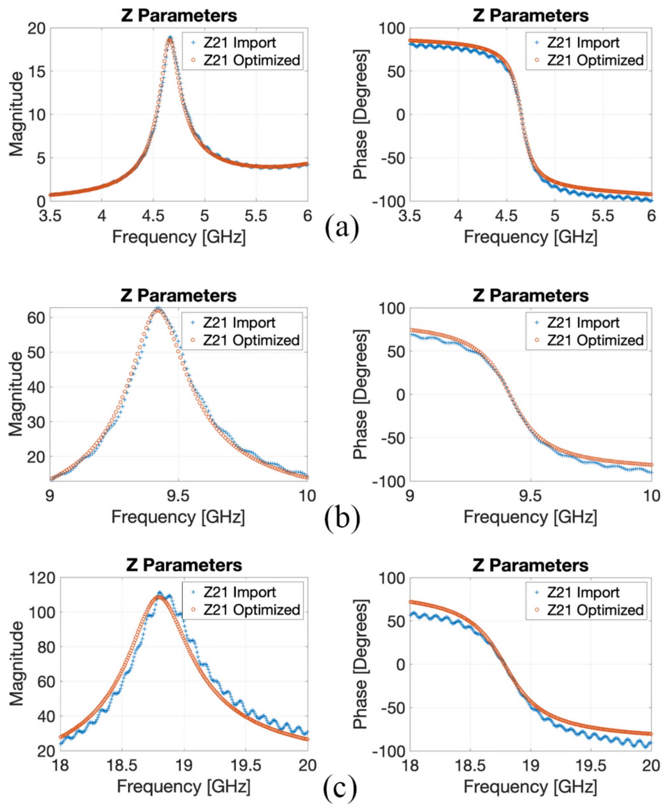

Fig. 4. Overlay of imported measurement and optimized simulation of flip-chip underfill using Kappa Extractor. Transverse electric field mode TE_{101} magnitude and phase of (a) resonator 1 at 4.70 GHz, (b) resonator 2 at 9.44 GHz, and (c) resonator 3 at 18.84 GHz.

TABLE I
EXTRACTION RESULTS FOR FLIP-CHIP UNDERFILL

Frequency [GHz]	HFSS DK	Kappa DK	% Diff. DK	HFSS DF	Kappa DF	% Diff. DF
Resonator 1 (Largest)						
4.70	3.545	3.563	0.5%	0.03525	0.03502	-0.7%
7.45	3.458	3.506	1.4%	0.02785	0.02629	-5.6%
9.41	3.451	3.490	1.1%	0.02248	0.02068	-8.0%
Resonator 2						
9.44	3.439	3.469	0.9%	0.02075	0.01932	-6.9%
14.90	3.354	3.482	3.8%	0.02389	0.02080	-12.9%
18.81	3.339	3.482	4.3%	0.02715	0.02196	-19.1%
Resonator 3 (Smallest)						
18.84	3.377	3.442	1.9%	0.02588	0.02173	-16.0%
29.67	3.209	3.493	8.9%	0.05619	0.05801	3.2%

SIW resonators are constructed on the Roger's material are 6 mm in both the width and length from center-to-center of the via fence. These resonators are expected to resonate around 18.75 GHz for the dominant mode resonance frequency (TE_{101}). The two resonators measured on a VNA have different heights, one resonator is 300 µm thick and the other is 500 µm thick. The stack-ups are shown in Fig. 5 and Fig. 6.

The vias around the perimeter of the SIW resonator and the signal vias are 100 µm in diameter. The pitch of the via fence is 200 µm from center-to-center. The signal pad for probing is 150 µm in diameter. There is a spacing of 50 µm between the signal pad and the top ground plane. The copper plating

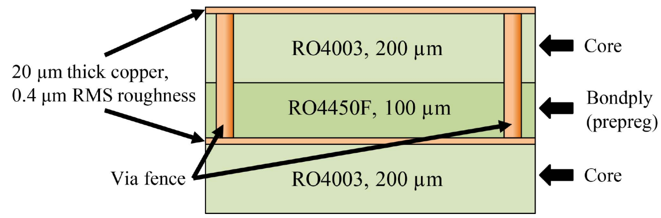

Fig. 5. Stack-up of 200 µm of RO4003 and 100 µm of RO4450F for a combined height of 300 µm.

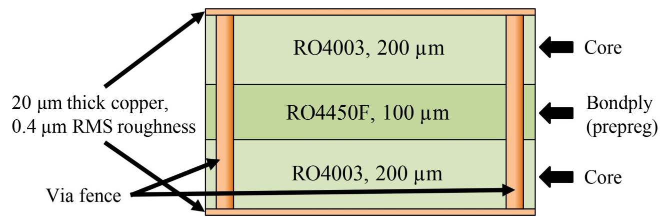

Fig. 6. Stack-up of 200 µm of RO4003, 100 µm of RO4450F, and 200 µm of RO4003 for a combined height of 500 µm.

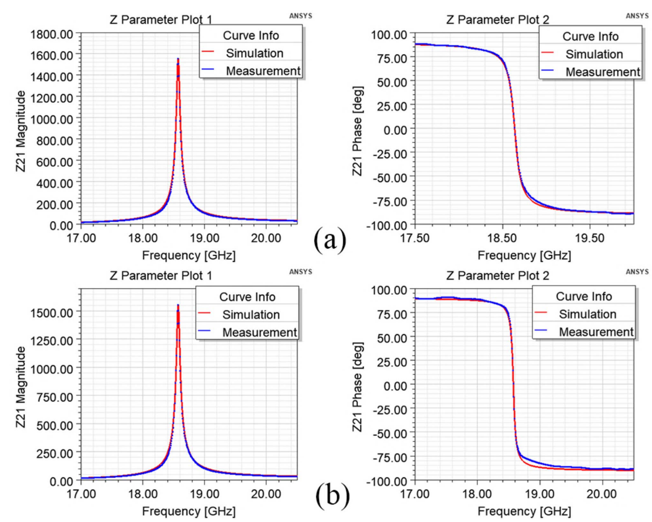

Fig. 7. Overlay of measurement and simulation using full-wave simulation. Transverse electric field mode TE_{101} magnitude and phase of (a) 300 µm height SIW resonator and (b) 500 µm height SIW resonator.

is 20 µm thick rolled copper with a root-mean-square (RMS) roughness of 0.4 µm.

B. Measurement of RO4003

Measurements were performed on a VNA with GSG micro-probes. Short-open-load-thru (SOLT) calibration was performed prior to measurement. Several measurements were performed on each SIW resonator with varying number of frequency points and the best measurements were selected for use in characterizing the dielectric.

C. Extraction Results of RO4003

Using both full-wave simulation and Kappa Extractor, the dielectric constant and loss tangent were extracted. The first two resonances where measured on the 300 µm and 500 µm cavities. These two resonant modes are TE_{101} and TE_{102} or

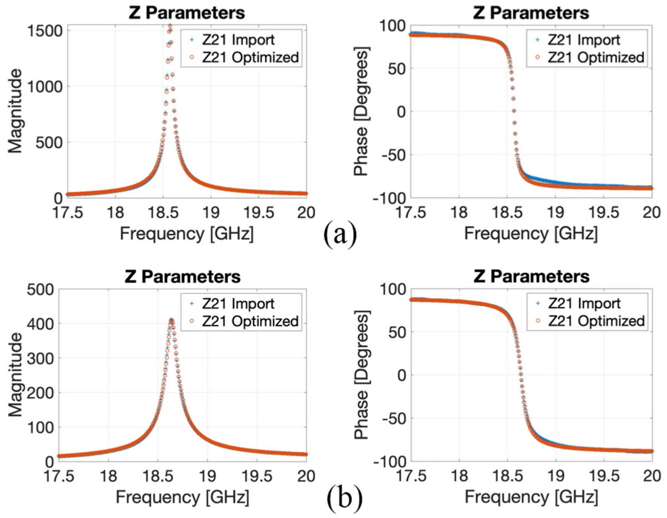

Fig. 8. Overlay of imported measurement and optimized simulation using Kappa Extractor. Transverse electric field mode TE_{101} magnitude and phase of (a) 300 µm height SIW resonator and (b) 500 µm height SIW resonator.

TABLE II
EXTRACTION RESULTS FOR ROGERS RO4003

Frequency [GHz]	HFSS DK	Kappa DK	% Diff. DK	HFSS DF	Kappa DF	% Diff. DF
Resonator 1 (300 um)						
18.64	3.633	3.583	-1.4%	0.00230	0.00283	23.0%
29.24	3.597	3.639	1.2%	0.00812	0.01055	29.9%
Resonator 2 (500 um)						
18.57	3.608	3.613	0.1%	0.00113	0.00085	-24.8%
28.65	3.568	3.797	6.4%	0.01266	0.01098	-13.3%

TE_{201}. Overlay of simulation and measurement is shown for the dominant mode resonance (TE_{101}) of each SIW resonator in Fig. 7 and Fig. 8.

Good alignment is seen between the measurement and simulation of the 300 µm height cavity. Meanwhile, the 500 µm height cavity shows a slight deviation. This is likely due to the fact that the RO4003 and RO4450F layers are modeled and simulated as one homogenous medium and one effective dielectric constant.

The results obtained using both full-wave simulation and Kappa Extractor are shown in Table II. The SIW resonator height used in Kappa Extractor and full-wave simulation are different and contribute to the deviation seen between the results of the two different solvers. Other sources of error in Kappa Extractor include the simplifications made when using the rapid plane solver, assuming that perfect electric conductor is placed at the walls of the SIW resonator and that the signal pins are point sources. In addition, the SIW resonator is modeled in full-wave simulation with a via fence, whereas, in Kappa Extractor it assumes that there are solid walls of perfect electric conductor in place of the via fence. Furthermore, any radiating fields that escape through the via fence are not accounted for in Kappa Extractor.

The dielectric constant extracted in Kappa Extractor for both SIW resonators is within 7% of what was determined from full-wave simulation up to 30 GHz. The loss tangent extracted in Kappa Extractor for both SIW resonators is within 30% of what was determined from full-wave simulation up to 30 GHz.

V. Conclusion

We characterized a flip-chip underfill material and a low-loss packaging material using an in-house automated tool called Kappa Extractor. The extracted dielectric constant using Kappa Extractor agreed within 9% with the extracted values using full-wave simulation up to 30 GHz. The loss tangent showed larger deviation due to the different cavity heights used between simulators, the simplification of assuming perfect electric conductor at the walls along the height of the resonators in Kappa Extractor, and the point source excitation used in Kappa Extractor.

Ultimately, Kappa Extractor provides a quick way to characterize dielectrics with a reasonable amount of accuracy. This is useful for characterizing new or existing materials at microwave and millimeter-wave frequencies. Kappa Extractor provides a simpler and faster method to characterize dielectrics.

Acknowledgment

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