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96-GHz Complementary Split Ring Resonator for Thin Photoresist Film Thickness Characterization

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***Abstract*— Non-destructive thickness measurement offers a valuable feature for thin polymer-based applications in both industrial and medical utilization. Herein, we developed a novel, non-destructive, millimetre-wave WR-10 waveguide sensor for measuring a dielectric film layer on a transparent substrate. Complementary split-ring resonator (CSRR) was integrated on top of a customized WR10 waveguide and operated at 96 GHz. The thickness of the SU-8 layers, ranging from 3-13 µm, coated on a glass substrate was then examined using the resonant frequency shift. The thickness values obtained from this novel sensor strongly resemble the values obtained from standard surface profiler measurement method, with less than 5 % difference. Thus, our novel design offers a comparable accuracy with a better cost effectiveness when compare with an existing commercial instrument.**

***Keywords— Non-destructive measurement, millimeter-wave sensor, SU-8 photoresist, tailor-made W-band waveguide, thickness characterization*.**

I. INTRODUCTION

Thickness measurement of dielectric and polymer structures is an important process in many industrial and medical applications [1]-[4]. Several techniques for thickness characterization have been developed. Among them, surface profile analysis and white-light interferometry are perhaps the two most widely used methods.

Surface profile analysis utilizes the stylus needle to assess the thickness of a deposited dielectric film. Despite its high accuracy, this technique does have some serious drawbacks. Because this technique requires a physical contact between the stylus and the sample, it could potentially cause damage to the surface of the sample if excessive force is applied to the needle. In addition, this technique is time-consuming as the samples must be loaded and unloaded individually with care to prevent any damages to the stylus. Moreover, this method is also sensitive to mechanical vibration and thus it requires special damping measures.

The white-light interferometer has been recently developed to offer a better resolution when compare to the surface profiler, hence, it is mostly employed in high-precision applications. The major disadvantage of this method is its high operation cost; this expensive instrument also requires a large floor space as well as specialized operators. Furthermore, it is even more sensitive to mechanical vibration when compare with the surface profiler. Also, another critical flaw of this method is the requirement for all photoresist samples to be fully exposed to UV light prior to their measurement to prevent any alterations of their property by white light throughout the analysis.

Herein, we describe an establishment of an alternative, non-destructive method to characterize the thickness of dielectric film layers on glass or quartz substance. A customized, waveguide-based sensor with a single complementary split ring resonator (CSRR) was designed and used to determine the thickness of the photoresist films by analyzing the change in the resonance frequency of the CSRR due to dielectric loading. We also demonstrate here that this novel approach provides several advantages over existing tools. First, this new method is mostly automated and thus it is more user-friendly and does not require specially trained staff to run the analysis. Secondly, its sensors are less expensive and faster to manufacture. Thirdly, the setup of this instrument only requires a small space and can be relocated due to its tolerance to mechanical vibration. Fourthly, there is no restriction on ambient light condition. Lastly, lower risk for surface damage as no physical contact between the sensor and samples is needed.

II. WORKING PRINCIPLE, SENSOR DESIGN AND FABRICATION

This design relies on the use of a single CSRR which is assembled on the top broad wall of a customized, H-plane, split WR-10 waveguide block that operates at 75-110 GHz. Samples can be aligned individually on a 3D-printed fixture located above the CSRR.

A. Working Principle

The fundamental of this instrument depends on a single-port, *S*-parameter measurement which works to reflect and radiate an interaction between a standing electromagnetic (EM) wave and a dielectric sample.

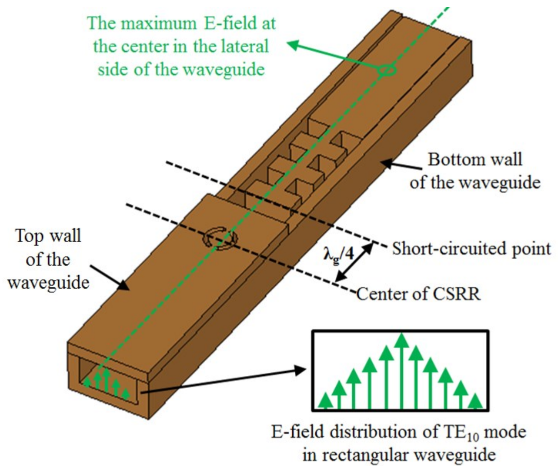

Fig. 1. The CSRR slot is fixed to the lateral dimension of the waveguide to obtain the highest electromagnetic radiation in fundamental TE mode (TE_{10}). The short-circuited termination is inserted to one port on the sensor that the distance between this termination and the CSRR is kept at λg/4.

The design of the waveguide sensor used in this resonance technique relies on an insertion of a short-circuited termination on one of the rectangular waveguide ports. The Fig.1 shows the distance between this termination and the CSRR, which is kept at $\lambda_g/4$, where λ_g is the wavelength of EM signal propagating inside the waveguide at the nominal resonant frequency of 96 GHz. This frequency is also referred as a nominal resonant frequency (f_r) where a minimum in the reflected EM energy, $|S_{11}|$, is observed due to the radiation of EM-wave into a free space.

In the presence of a multilayered dielectric sample, *e.g.* a thin-film dielectric layer on the surface of a substrate, a shift in resonant frequency due to the dielectric loading of the resonator can be observed and this shift strongly correlates with the thickness and relative permittivity of the sample.

B. *Complementary Split Ring Resonator Design*

The CSRR is placed onto the top wall of a 0.5 mm-thick, copper waveguide. To obtain the highest electromagnetic radiation of the resonator in fundamental TE mode (TE_{10}) of the waveguide, the resonator is fixed to the lateral dimension of the waveguide to enhance the electrical field around the CSRR slot. The 2D drawing of the top wall of the waveguide with CSRR and the equivalent circuit model of the CSRR are shown in Fig 2(a) and Fig. 2(b), respectively. The capacitance, C_1, depends on the slot width and length while the metal strips denoted as "gap" is responsible for the inductance, L_1. These strips link the inner metal patches to the rest of the sheet at the top and the bottom of the CSRR. Lastly, the resistance, R, indicates the loss of the CSRR and is used to fine-tune the resonant frequency in the reflection coefficient (S_{11}).

C. *3D-Printed Fixture Structure*

In this design, we utilize a 3D-printed fixture as a stable platform for sample alignment to prevent EM interference to the CSRR and thus maximize repeatable comparisons between SU-8 layers coated at different thickness on glass substrates. This 3D fixture prototype was made from Polylactic acid (PLA) using a CEL Robox RBX02 Dual Material 3D printer out of 1.75 mm diameter PLA filament, using the finest available layer resolution.

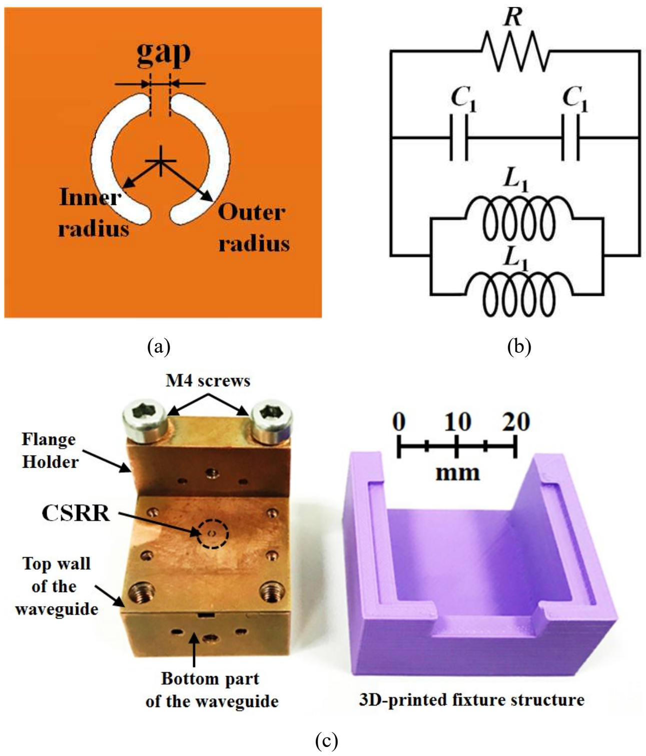

Fig. 2. (a) 2D drawing of the top wall of the waveguide with a CSRR slot, (b) the equivalent circuit model of the CSRR, and (c) Fabricated sensor, consisting of a single CSRR machined into the top broad wall of the integrated sensor prototype and 3D-printed fixture.

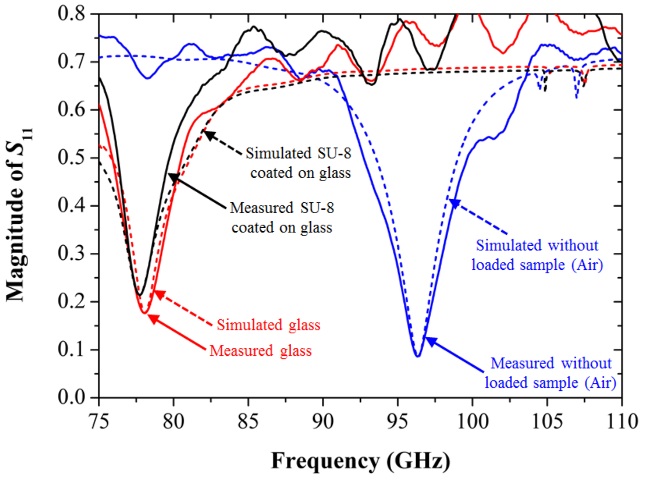

Fig. 3. Simulated and measured magnitude of S_{11} results, for unloaded sample of CSRR (Air), glass, and SU-8 coated on glass.

D. *Fabrication and Integration Structure*

The individual parts of the sensor were fabricated in the EPSRC National Facility for Innovative Robotic Systems at the University of Leeds.

The bottom part of the waveguide located a full-size WR-10 waveguide channel is made from a single copper block using a 5-axis DMU 40 CNC milling machine. The top part is fabricated separately out of a 0.5 mm-thick copper sheet with the CSRR etched into it by using LPKF ProtoLaser U3. This prototype is designed is to maximize the cost effectiveness by allowing a customization of top lid sheets with different resonators to be used with a single bottom part. The flange holders located on one end of the sensor were fabricated from a smaller copper block. More information regarding the tailor-made WR10 waveguide fabrication can be found in [3]-[4].

Complete assembly of the sensor is shown in Fig. 2(c). Briefly, two M4 screws were fastened to secure the flange holder and the top wall to the bottom part, reducing air gaps in the H-plane to ensure good EM performance. A standard UG-387/U-M flange is implemented. The 3D printed fixture was then locked to the waveguide sensor with double-sided adhesive tape. For a final step, the assembly is mounted onto a vertical positioner for a proper connection with the *S*-parameter measurement equipment.

III. THICKNESS CHARACTERIZATION MODEL

A. Sensor Optimization and Material Characterization

The initial design was generated using a 3D EM simulation tool, CST Studio Suite, to obtain the dimensions of the CSRR with the resonant frequency, f_r, of 96 GHz. The first prototype exhibited an f_r shift from 96 GHz to 96.38 GHz when tested for $|S_{11}|$. This is most likely due to dimension tolerance inaccuracy from the fabrication process. To fix this issue, actual dimensions of the sensor were assessed under high magnification optical microscope and their $|S_{11}|$ results were then compared with the results from simulation as shown in Fig. 3.

For developing a thickness characterization model composed of SU-8 2000 series photoresist and standard lab-grade glass substrates, data on the dielectric properties of these two materials at the frequency band of interest, i.e. 75-110 GHz, is needed to better understand the relative permittivity of glass and SU-8 2000. This process consists of the following steps:

- Measure the thickness of a glass substrate using an Alpha-Step IQ surface profiler.
- Measure the S_{11} parameter by loading CSRR sensor on the same glass substrate.
- Precisely model the physical dimensions of the glass substrate in CST Studio Suite and optimize the value of its relative permittivity until there is a match in the resonant frequency in the $|S_{11}|$, and optimize the value of its loss tangent to match in the magnitude of $|S_{11}|$.
- Repeat steps 1-3 and change the sample loading to a layer of 13.56 µm-thick SU-8 deposited on top of a 160.5 µm-thick glass substrate.

In this experiment, the relative permittivity and loss tangent of a glass substrate for W-band were 4.10 and 0.045, respectively. While the relative permittivity and loss tangent of SU-8 2000 were 3.22 and 0.025, respectively. Of note, this result of SU-8 2000 was strongly comparable to those previous published in [4].

B. Glass Thickness Characterization

Establishment of the numerical technique to determine the thickness of glass substrate from $|S_{11}|$ measurements was also developed using CST Studio Suite.

Briefly, the analysis was performed followed the step in Section III-A, with the value for relative permittivity and loss tangent of glass fixed to 4.10 and 0.045, respectively. Next, the thickness of glass substrate was increased by 1 µm each round with the final thickness ranging from 145 µm to 175 µm. The resonant frequency in $|S_{11}|$ was recoded and plotted

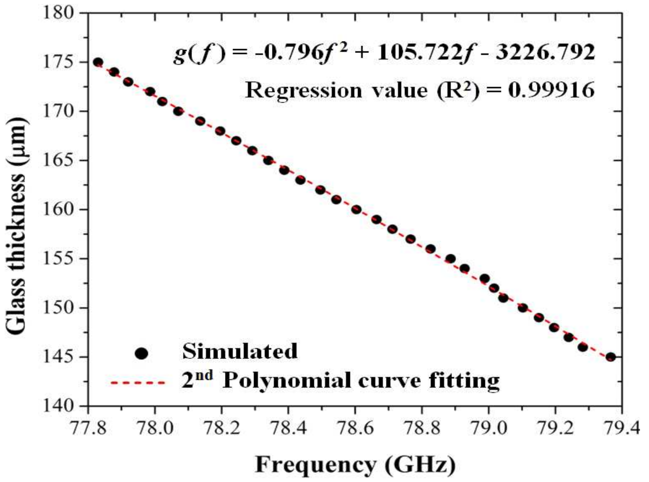

Fig. 4. The resonant frequency in $|S_{11}|$ was plotted as a function of glass substrate by varying glass thickness from 140 – 175 µm. The second order polynomial line was fitted to offer the best relation with regression value of 0.99916.

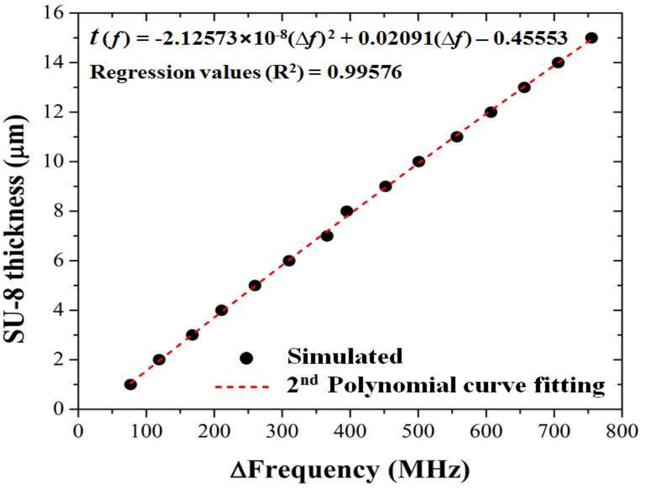

Fig. 5. The resonant frequency change in $|S_{11}|$ was plotted as a function of SU-8 layer thickness by varying thickness from 1 – 15 µm. The second order polynomial line was fitted to offer the best relationship with regression value of 0.99576.

as a function of glass substrate thickness in Fig. 4. These individual data points were then fitted into a polynomial using a commercially-available data analysis and visualization software package, Origin, where a second order polynomial was found to offer the best fit with regression value R^2 of 0.99916. The polynomial is given as:

$$g(f) = -0.81f^2 + 106.24f - 3230.55 \tag{1}$$

where $g(f)$ is the glass substrate thickness in µm as a function of the resonant frequency, fr, GHz. A comparison between the fitted and measured values is also shown in Fig. 4. Eqn. (1) can now be used to determine the thickness of glass substrate samples.

C. SU-8 Thickness Characterization

Thickness of SU-8 layers was assessed using a similar approach as described in IIIB. Briefly, a correlation between thickness of SU-8 2000 and the resonance frequency shift $|\Delta f| = |f_r(\text{SU-8})| - |f_r(\text{glass})|$ was performed. The thickness of SU-8 layers was varied between 1 – 15 µm (1-µm step interval) with a constant glass thickness of 160.5 µm. A

TABLE. I EXTRACTED RESULTS OF FIVE GLASS SUBSTRATE THICKNESSES

No.	**Measured resonance frequency (GHz)**	**Extracted glass thickness from (1) (µm)**	**Measured glass thickness from Alpha-step (µm)**	**% Difference**
1	78.955	153.0715	152.75	0.2105
2	78.815	155.8708	155.75	0.0776
3	78.670	158.7176	158.20	0.3272
4	78.570	160.6946	160.50	0.1212
5	78.500	162.0552	161.75	0.1887

TABLE. II EXTRACTED RESULTS OF FIVE SU-8 LAYER THICKNESSES

No.	**Measured resonance frequency change, Δf_r (MHz)**	**Extracted SU-8 layer thickness from (2) (µm)**	**Measured glass thickness from Alpha-step (µm)**	**% Difference**
1	140	2.4715	2.50	1.14
2	210	3.9346	3.75	4.92
3	315	6.1290	6.33	3.18
4	525	10.5164	10.20	3.10
5	665	13.4402	13.56	0.88

second order polynomial showed a regression value R^2 of 0.99576. The polynomial is given as:

$$t(f) = -2.26\times10^{-8}(\Delta f)^2 + 0.0211\Delta f - 0.456 \qquad (2)$$

where $t(f)$ is SU-8 thickness in µm as a function of Δf_r, which is in MHz. A comparison between the fitted and measured values is shown in Fig. 5. Equation (1), together with Eqn. (2) can be used to determine thickness of samples composed of a glass substrate and a SU-8 2000 layer with unknown thickness.

IV. RESULTS

A. Measurement Setup

S-parameter measurement was achieved through a Keysight PNA-X N5242A with OML WR-10 VNA Extender Heads. The measurement was obtained from all available frequency range of WR-10 (75-110 GHz), and was compared with those obtained from Alpha-Step IQ surface profiler [6] for validation purposes. A calibrated drop-down micrometer was also used to confirm the Alpha-Step IQ results.

B. Glass Substrates Thickness Measurement

As shown in Table I, extracted glass thickness values from our method are closely resembled the values obtained from Alpha-Step IQ surface profiler; only slight percent difference was observed. This data, therefore, validate our method and confirm its accuracy to be comparable to the standard measurement technique.

C. SU-8 Layer Thickness Measurement

Five samples of glass substrate with various SU-8 thickness layers, 2.50 µm, 3.75 µm, 6.33 µm, 10.20 µm, and 13.56 µm as judged by Alpha-Step IQ. The thickness of each sample was then extracted using the following steps:

- Measure the thickness of uncoated and SU-8 coated glass and record the resonant frequency in a magnitude of S_{11}.
- Determine Δf_r of SU-8 coated glass to an uncoated one.
- Substitute Δf_r values in Eqn. (2) to calculate the thickness of SU-8 layers.

The results from this experiment were shown in Table II. Only 4.92% thickness difference was observed between our newly design sensor and Alpha-Step IQ. This data strongly supports the accuracy and precision of our novel sensor design to be comparable to the standard measurement.

V. CONCLUSION

A novel design for thin-film thickness characterization sensor was developed. This newly-designed sensor operated at WR-10 millimeter-wave band utilizes a single CSRR to collect reflected electromagnetic waves, propagated inside the waveguide, which are altered due to the change in relative permittivity which mirror the thickness of the samples.

Its performance of this design was comparable to the standard commercial surface profiler with an accuracy of 95%. It is also proved to minimize the operating cost and space, lessen the operating time, offer a contactless mode, and provide a potential application on unexposed and non-baked photoresist layers.

ACKNOWLEDGMENT

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