Assessing the Impact of Data Filtering Techniques on Material Characterization at Millimeter-Wave Frequencies

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***Abstract*— This article reports on an investigation into data filtering techniques for material characterization using a commercially available WR-15 (50–75 GHz) material characterization kit (MCK). The MCK uses a guided free-space method (operating like the conventional quasi-optical focused beam system) that enables measurement of *S*-parameters of dielectrics using a vector network analyzer (VNA). Multiple reflections and resonances exist in the MCK and they cannot be readily eliminated by calibration. To minimize these effects on extracting dielectric constant and loss tangent from the measured *S*-parameters, data filtering techniques (e.g., Savitzky–Golay filter and time-gating) can be adopted. A comparison of the measurement results using these two techniques was carried out on five common dielectric materials. Generally, the results obtained using these two filtering techniques are consistent with each other, and the Savitzky–Golay filter offers better performance in the scenario where the specimen quality is not ideal. Three specimens were also measured using an open resonator (operating at 36 GHz). There is generally good agreement between the results from the MCK and the open resonator.**

***Index Terms*— Data filtering, dielectric constant, loss tangent, millimeter-wave measurements, time-domain gating, vector network analyzer (VNA).**

I. INTRODUCTION

THE millimeter-wave spectrum has been actively exploited by a range of applications including backhaul and fronthaul for 5G communications, space-borne radiometers for earth remote sensing, automotive radar sensors, and so on. This has driven the demand for accurate characterization of material properties, that is, dielectric constant, ε', and loss tangent, tan δ. Material characterization has also been widely used in the development of various types of sensors for solid and liquid materials (see [1]). There exist many different material characterization methods [2], and among them some popular methods are (presented roughly in order of increasing frequency) split-post dielectric resonators [2]–[3], coaxial probes [4], transmission lines [5], open resonators [6], [7], free-space methods [8], [9], and time-domain spectroscopy (TDS) methods [10]. The open resonators and free-space methods have been most widely used for measurements at millimeter-wave frequencies. For open resonators, ε' is measured by a frequency change and tan δ is determined from the *Q*-factor, on insertion and removal of the specimen. Open resonators provide the most accurate measurement of low-loss dielectrics at millimeter-wave frequencies, due to the ultrahigh unloaded *Q*-factor of the resonator (greater than 200 000 at >100 GHz [2]). However, this method requires the specimen thickness to be approximately an integral number of half-wavelengths (in the medium of the dielectric) and the specimen diameter to be greater than 5 times the radius of the Gaussian beam, used during measurement, at the beam's waist. Free-space methods are broadband and typically rely on elements such as parabolic mirrors or lenses to prevent divergence of the Gaussian beam. For free-space methods, ε' and tan δ are usually determined from the measured transmission response (i.e., complex S_{21} or S_{12}) of the specimen.

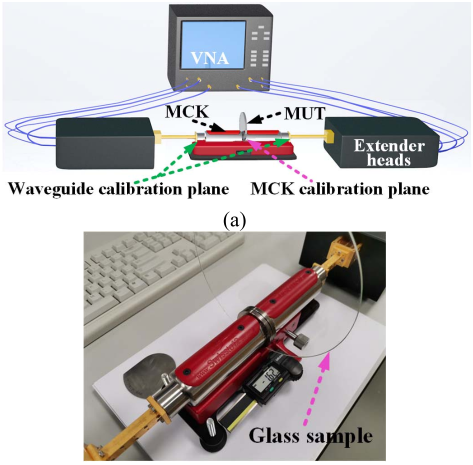

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Fig. 1. (a) Configuration for the MCK measurement system comprising a WR-15 MCK, a pair of VDI WR-15 frequency extender heads, and a Keysight PNA-X N5247B VNA. (b) Photograph of the WR-15 MCK measurement setup, showing a glass sample sandwiched between the two MCK test ports.

Recently, a new guided free-space method based on material characterization kits (MCKs) [11] has been developed by SWISSto12. Fig. 1 shows a WR-15 band MCK system at the National Physical Laboratory (NPL), U.K. This MCK comprises rectangular to corrugated waveguide transitions and

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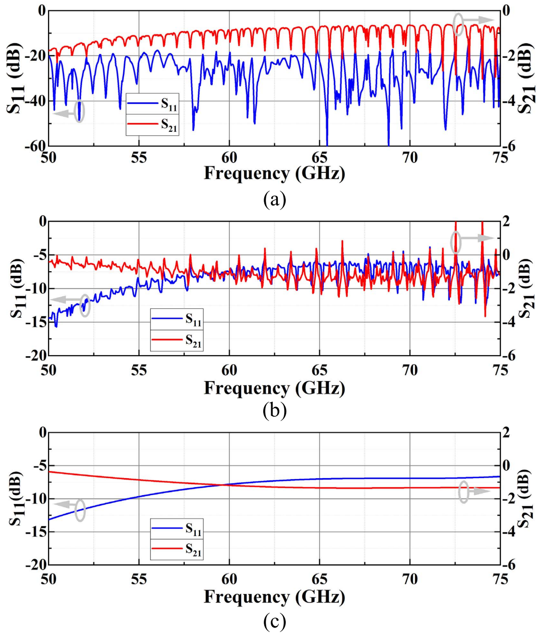


Fig. 2. (a) S-parameter response of the WR-15 MCK with Thru connection, after waveguide SOLT calibration. (b) Response of an acetal co-polymer sample (thickness 2.03 mm), after TRL calibration of the MCK. Time-gating was not applied. (c) Response of the acetal co-polymer sample after time-gating was applied.

sections of low-loss corrugated waveguides (with inner/outer diameters of 20/22.49 mm). The corrugated waveguides operate at the HE_{11} mode and are capable of launching high-purity (>98%) Gaussian beams. During the measurement, the specimen is sandwiched between two corrugated waveguides and the S-parameters of the specimen can be captured and used for calculation of ε' and tan δ. In contrast to the conventional quasi-optical free-space system, the MCK system is compact and self-contained, eliminating the need for bulky mirrors or lenses. MCKs have been successfully utilized for material characterization at millimeter-wave and terahertz frequencies [11]–[13].

There are spurious signal reflections inside the MCK, which persist even after calibration. Fig. 2(a) shows the response of the WR-15 MCK, when the two test ports of the MCK are connected directly. A waveguide short–open–load–thru (SOLT) calibration was performed prior to the measurement; see Fig. 1(a) for the waveguide calibration planes. The MCK has low insertion loss (∼1.3 dB, averaged across the waveguide band); however, there are considerable resonances in both the S_{11} (or S_{22}) and S_{21} (or S_{12}) responses. These resonances make a direct impact on subsequent measurements of the S-parameters of the samples. For example, Fig. 2(b) shows the response of a 2.03-mm-thick acetal co-polymer sample, following a free-space thru–reflect–line (TRL) calibration at the MCK calibration plane [12]. The traces are somewhat erratic, and therefore further corrections for this effect must be incorporated into the measurement method.

Filtering measured data with a time-domain gate [14] is effectively applying smoothing to the measured data. This has been recommended by the manufacturer and used in most previous work [11], [12]. However, the use of time-gating can be undesirable for some measurement scenarios (e.g., when propagation of measurement uncertainty is of interest).

Here, we have investigated an alternative data filtering technique based on the Savitzky–Golay filter [15], which avoids the use of time-gating. This article describes a comparison of these two filtering techniques carried out using five common dielectric materials, that is, acetal co-polymer (thickness 2.03 mm), PTFE (thickness 11.98 mm), glass (thickness 1.62 mm), quartz (thickness 4.13 mm), and LDPE (thickness 6 mm). For validation purposes, the last three samples have also been measured on a 36-GHz open resonator (using a well-established system at NPL operating at a frequency close to the WR-15 band). To the best of the authors' knowledge, this is the first time that Savitzky–Golay filtering has been applied to reduce the effect of multiple reflections associated with the MCK. An open resonator (the most accurate method at millimeter-wave frequencies) has also been used, for the first time, for benchmarking the measurement results obtained using the MCK.

II. DATA FILTERING TECHNIQUES FOR MCK MEASUREMENTS

A. Time-Gating

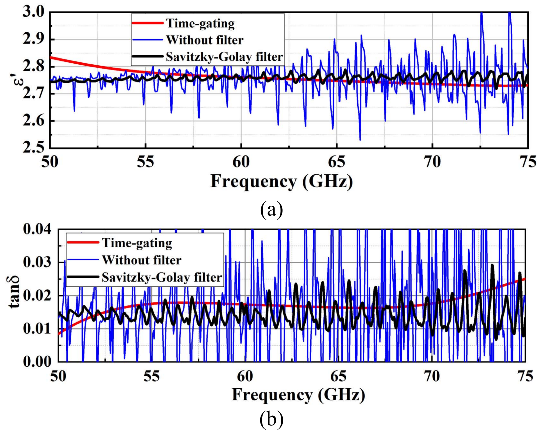
Time-gating is usually applied to free-space measurements to separate the desired signal from spurious reflections generated elsewhere in the measurement system or within the sample [16]. A Kaiser–Bessel window is introduced in the time-domain so that signals that are not within the bandpass window are discarded. The processed time-domain signal is then converted into the S-parameters for calculation of ε' and tan δ. For MCK measurements, it is also recommended by the manufacturer to use time-gating, and the gate width is usually specified as 400 ps. In practice, the optimum gate width varies with the characteristics of the measured specimen and can be calculated from the approximate dielectric constant, sample thickness, and operating frequency [11].

In this work, the time-gating widths for acetal co-polymer, glass, quartz, LDPE and PTFE were calculated, using the midband frequency of 62.5 GHz, to be 68, 140, 230, 180, and 339 ps, respectively. Fig. 2(c) shows the S_{11} and S_{21} responses of the acetal co-polymer sample after time-gating was applied. Compared with the response in Fig. 2(b), time-gating has effectively cleaned up the data. Fig. 3 shows the extracted ε' and tan δ, of the acetal co-polymer sample, using the time-gated S-parameters in Fig. 2(c). In this work, ε' and tan δ have been extracted from S_{21} (or S_{12}) by iteration [17]. The reflection responses, S_{11} (or S_{22}), are more prone to errors and therefore were not used.

B. Savitzky–Golay Filter

Savitzky–Golay filter is a filtering method based on local polynomial least squares fitting. The biggest feature of this filter is that it smooths traces while preserving their overall shape. Window points and polynomial orders are the most important features for the Savitzky–Golay filter. In this work, 51 window points and second-order polynomial fitting have been chosen and used to process results, as they offer the optimum performance in terms of smooth and linear curves for the extracted ε' and tan δ.

Fig. 3 shows the extracted ε' and tan δ of the acetal co-polymer sample, using the Savitzky–Golay filter.



(a)

(b)

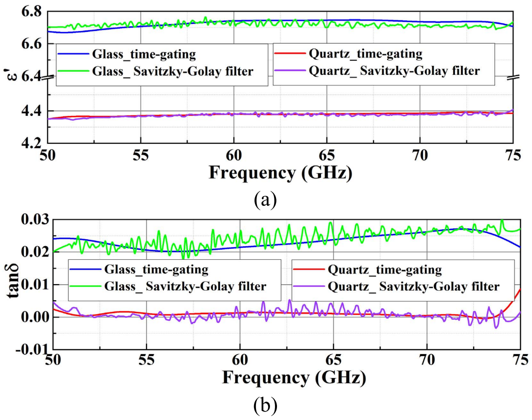
Fig. 3. Extracted (a) ε' and (b) tan δ for the acetal co-polymer sample. Results from time-gating and with/without Savitzky–Golay filter are included for comparison.

The S-parameters shown in Fig. 2(b) were used in the calculation and the obtained ε' and tan δ were processed using the Savitzky–Golay filter. Fig. 3 also includes the results without Savitzky–Golay filter, which show significant resonances. For both time-gating and Savitzky–Golay filter, S-parameter measurements were made from 47 to 78 GHz using a VNA with 30-Hz IF bandwidth and 1000 frequency points. The measurements were made in a temperature-controlled laboratory specified at (23 ± 1) °C. Both the results were subject to a free-space TRL calibration [12] performed at the MCK calibration planes. Only the results from 50 to 75 GHz (i.e., the usual bandwidth for WR-15) have been produced and shown here, as both filtering techniques suffer from band-edge effects. These two data filtering techniques have been applied to the same set of S-parameter data, to avoid any influences coming from other factors (such as connection repeatability).

III. RESULTS

A. Comparison Between Time-Gating and Savitzky–Golay Filter

Similar comparisons have been carried out using glass, quartz, LDPE, and PTFE samples, and the results are shown in Figs. 4 and 5. To reduce the effect of random errors, the MCK measurements were repeated six times. The results presented in this article are the average of these six repetitions. Generally, there is a good agreement between the results of Savitzky–Golay filter and time-gating, particularly for thicker samples (i.e., quartz, LDPE, and PTFE). The results of acetal co-polymer and glass show a relatively large difference, as shown in Figs. 3 and 4. For the acetal co-polymer sample, at 50 GHz, ε'/tan δ related to time-gating and Savitzky–Golay filter is 2.834/0.008 and 2.744/0.015, respectively, as shown in Fig. 3. There is systematic variation with frequency for the time-gating results, particularly for the acetal co-polymer sample, and this does not agree with the expected physical behavior (i.e., ε' of homogeneous and noncomposite dielectric materials should exhibit a linear response to frequency [2]). The difference is believed to be attributable to imperfections in the specimen (in terms of poor flatness and the resulting localized air gaps during measurement), due to the small sample thickness (2.03 mm for acetal co-polymer and 1.62 mm for glass) and the large diameters. Systematic errors in the measured S-parameters of a material under test (MUT) exist due to factors such as: 1) unwanted air gaps present at the interfaces between the MUT and the MCK test ports and 2) unwanted couplings between these test ports. Such errors could result in apparent unphysical behavior, observed in the time-gating results, and oscillations in the Savitzky–Golay filter results.



(a)

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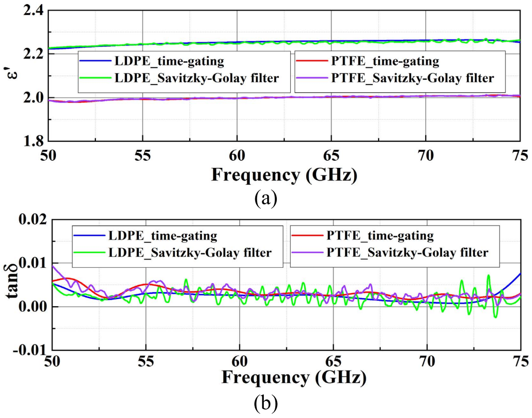
Fig. 4. Extracted (a) ε' and (b) tan δ, for the glass sample and the quartz sample, using time-gating and Savitzky–Golay filters.



(a)

(b)

Fig. 5. Extracted (a) ε' and (b) tan δ, for the LDPE sample and the PTFE sample, using time-gating and Savitzky–Golay filters.

Note that the sizes of these samples utilized in this work were optimized for measurement using open resonators, and that is why they have large diameters and small thicknesses for some. Additionally, the rapid oscillations in the Savitzky–Golay filter results, as shown in Figs. 3 and 4, can be reduced by optimizing the window points and the order of polynomial fitting. This work intends to report the Savitzky–Golay filter results for all five samples using the same settings, and therefore optimization was not undertaken for each individual sample. The results for these five samples indicate that the Savitzky–Golay filter provides an alternative method to the time-gating method. The Savitzky–Golay filter performs better for poor quality specimens (with degraded accuracy in the measured S-parameters). In addition, the Savitzky–Golay filter does not require prior knowledge about the dielectric constant of the sample, or, for the VNA to have a time-domain capability.

TABLE I
COMPARISON OF ε' VALUES

Sample	MCK (Time-gating)	MCK (Savitzky-Golay filter)	Open-resonator
LDPE	2.253 ± 0.040	2.250 ± 0.038	2.286 ± 0.005
Glass	6.727 ± 0.059	6.718 ± 0.044	6.70 ± 0.04
Quartz	4.378 ± 0.037	4.374 ± 0.041	4.433 ± 0.013

TABLE II
COMPARISON OF tan δ VALUES

Sample	MCK (Time-gating)	MCK (Savitzky-Golay filter)	Open-resonator
LDPE	0.002 ± 0.013	0.002 ± 0.013	0.00023 ± 0.00001
Glass	0.023 ± 0.014	0.024 ± 0.015	0.0221 ± 0.0012
Quartz	0.001 ± 0.012	0.0010 ± 0.013	0.000032 ± 0.000012

B. Comparison With Open Resonator

The extracted material properties of three of these samples (i.e., LDPE, glass, and quartz) were also compared with the results obtained on an in-house 36-GHz open resonator [6], as shown in Tables I and II. These specimens are in-house reference materials that are likely to exhibit bespoke behavior (i.e., not fully reproducible), and therefore comparisons with the literature were not considered appropriate. The thicknesses of the PTFE and acetal co-polymer samples were not compatible with the 36-GHz open resonator and hence were not measured.

As can be observed from Tables I and II, there is generally good agreement between values obtained by the MCK and open resonator. For the results obtained using the MCK, these tables give the average measured values (averaged across the full WR-15 band) for ε' and tan δ, with uncertainties established using an interval containing 95% of these values (as the type A component) combined with other uncertainty information presented in [11] (for the type B components). As shown in Fig. 1, the specimens for the open resonator are large in diameter and the MCK can only measure the part of the specimens around the edge. These samples have small thickness variations between the center and edge, leading to different specimen thickness being used (e.g., 4.12 mm for open resonator and 4.13 mm for MCK, for the quartz sample). This is believed to contribute to the differences observed between the results from the MCK and the open resonator.

IV. CONCLUSION

This article has assessed the impact of two data filtering techniques on material characterization using an MCK. It has been demonstrated that the Savitzky–Golay filter is as effective as, and sometimes superior to, the time-gating approach, in terms of minimizing the influence of spurious signals generated inside the MCK affecting the extracted material properties. The good agreement between the results obtained on the MCK and open resonator has validated the effectiveness of the MCK method and the data filtering techniques. Although the investigation was carried out at the WR-15 band, the filtering techniques described here are expected to show similar behavior for materials' measurements using MCKs operating at different waveguide bands or other free-space systems with poor matching (i.e., having inherent multiple reflections and resonances).

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