A comparison of measurements of the permittivity and loss angle of polymers in the frequency range 10 GHz to 90 GHz

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***Abstract*—The permittivity and loss angle of disc-shaped polymer specimens were measured by using three Split-Post Dielectric Resonators (9.5 GHz, 25 GHz & 34 GHz), a plano-concave open resonator (36 GHz), a bi-concave open resonator (20 GHz to 50 GHz), a helical cavity (10 GHz), and two free-space Gaussian-beam transmission systems (22 – 33 GHz & 60 – 90 GHz). The measured materials were PMMA, polycarbonate, THV 500GZ fluoropolymer, and two grades of PTFE. The work supports the need for materials for manufacture of components for 5G applications.**

***Index Terms*—dielectric permittivity, dielectric loss, SPDR, open resonator, quasioptic, measurements.**

I. Introduction

This paper presents a comparison of measurements of the permittivity and loss angle [1] of polymers by several different methods. Such data is needed for characterizing components use in 5G applications. Measurements were made by using three Split-Post Dielectric Resonators (SPDRs), a Helical Cavity (HC), two open resonators (ORs), and two Quasioptic (QO) transmission systems. Three laboratories were involved in the comparison. Vector Network Analyzers were used for making the measurements.

I. Specimens

Disc-shaped specimens were machined for each technique from the same batch of each material. The materials were:

PTFE

Two grades of the 3M™ Dyneon™ PTFE and TFM™ Modified PTFE families were used: Dyneon TF 1750 and Dyneon TFM 1700.

THV 500GZ

3M™ Dyneon™ Fluoroplastic THV 500GZ, which is a terpolymer that contains tetrafluoroethylene, hexafluoropropylene and vinylidene fluoride. This material has excellent flexibility, high optical clarity, and bondability, and can be processed at low temperatures.

PMMA and *polycarbonate*

The PMMA material for this study was purchased from McMaster-Carr. The polycarbonate material was purchased from Plastics Int.

II. Methods

A. Split-Post Dielectric Resonators (SPDRs)

SPDRs [2] enable measurements on low loss planar specimens to be made quickly and easily. Figure 1 shows a schematic of an SPDR. Permittivity and loss angle are determined from the resonant frequency and Q-factor of the quasi-TE01δ mode with and without the specimen. Each SPDR operates at only one frequency (determined by its dimensions). These measurements were performed at 3M. Specimens were machined to fit the resonators: Thickness 0.5 mm (9.5 GHz), 0.3 mm (25 GHz and 34 GHz).

B. Helical Cavity (HC)

Helical waveguide can be manufactured from a wire coil set inside a resin tube. It can propagate the TE_{01} mode with very low attenuation, but the degenerate TM_{11} mode is suppressed. The addition of metal end plates enables a cavity to be formed (Q-factor 50,000). In the NPL design [3], a piston that is moveable by means of a micrometer is used to tune the cavity (Figure 2). The empty cavity is tuned for resonance, then the specimen is inserted and the cavity is shortened to restore resonance. The permittivity and loss angle are calculated from the change in the cavity length and measured Q-factors. The specimens were half a wavelength thick in the medium of the material, in circular waveguide.

C. Bi-concave open resonator

The bi-concave Fabry-Perot OR was manufactured by EMArges Sp. z o. o., Warsaw. It allows automatic measurement of complex permittivity of thin dielectric materials at multiple frequencies in a 20 – 50 GHz range with a 1.5 GHz frequency step. The measurement of a single sample takes about 10 minutes. The Q-factor of the empty cavity reaches 200,000. Accuracy of the method based on a conformal transformation technique is better than 0.5% [4]. However, the largest source of uncertainty is usually due to uneven thickness of the sample.

D. Plano-concave open resonator

A plano-concave Fabry-Perot OR that resonates at frequencies in the range 30 GHz to 40 GHz was used. Measurements were made by the fixed-frequency tuneable length method [5]. Each specimen was measured at three modes, to check that measurements are not affected by coincident higher-order modes. The Q-factor of the empty cavity is approximately 130,000. The specimens were half a wavelength thick in the medium of the material. Uncertainties were evaluated from contributions associated with dimensions, Q-factors, and theory.

E. Free-space transmission

Quasioptic benches manufactured by Thomas Keating Ltd., UK, for 22 GHz to 33 GHz and 60 GHz to 90 GHz were used for measurement by transmission [6]. Calculability is improved by using corrugated horns that radiate Gaussian beams that are almost entirely in the fundamental mode. Results were calculated with Keysight N1500A software (“Polynomial Fit Transmission Epsilon” algorithm) [7]. A two-tier calibration process is used: a waveguide calibration followed by a Gated-Reflect-Line (GRL) calibration [8].

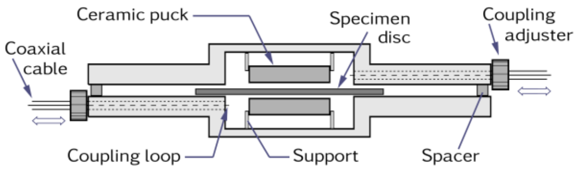


Figure 1: Split-Post Dielectric Resonator (used at 3M)

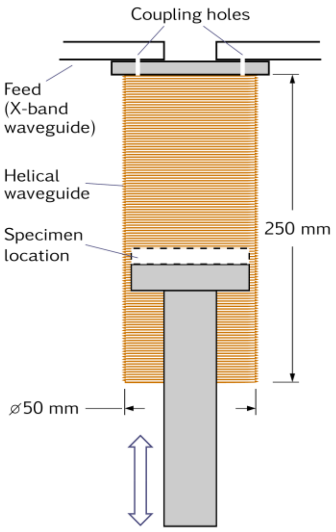


Figure 2: Helical cavity (used at NPL)

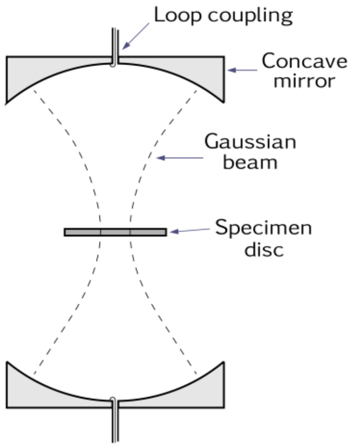


Figure 3: Bi-concave open resonator (used at W.U.T.)

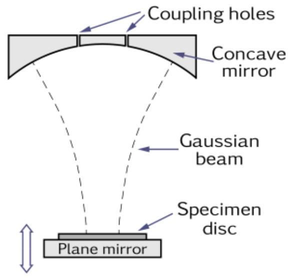


Figure 4: Plano-concave open resonator (used at NPL)

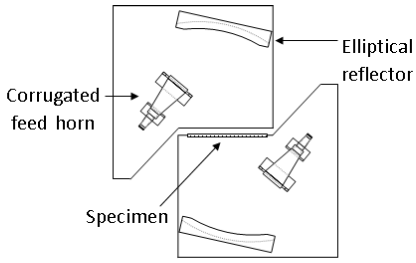


Figure 5: Free-space transmission system (used at 3M)

III. RESULTS

The measurements are shown in Tables 1–4 and plotted in Figures 6-9.

The dielectric loss is reported in terms of the *loss angle* (δ), which has units of milliradians. When δ is low valued then it is related to *loss tangent* (the ratio of imaginary and real parts of permittivity) by $\delta \approx \tan\delta \times 10^3$ milliradians. The Lynch formula [1] can be used to predict the change in permittivity between frequency f_1 and f_2:

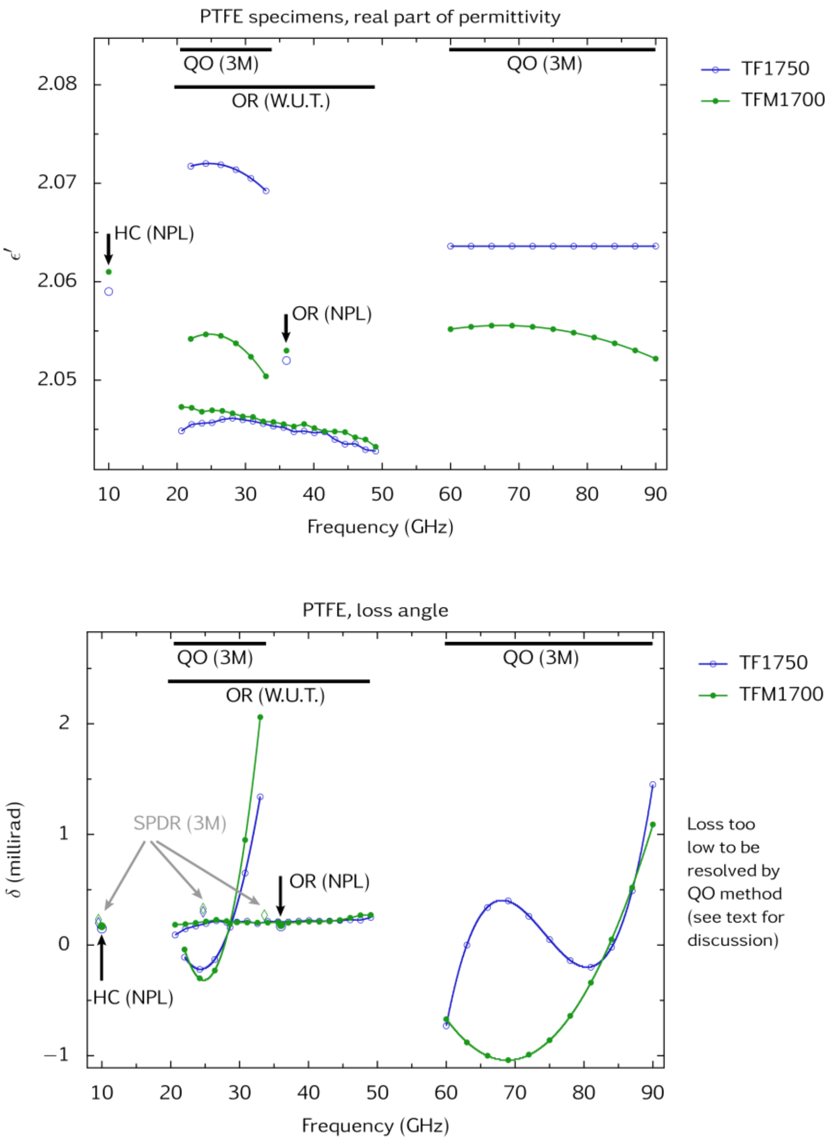


Figure 6: Measured permittivity and loss angle for two grades of PTFE.
Bracketed values are uncertainties at coverage factor k=2 (equivalent to approx. 95% confidence level).

Table 1: PTFE measurements

Method	Freq. (GHz)	TF1750		TFM1700	
		ε′	δ millirads	ε′	δ millirads
SPDR	9.5	2.042	0.2	2.051	0.2
Helical Cav.	10	2.059	0.2	2.061	0.2
SPDR	25	2.062	0.3	2.052	0.3
QO	27	2.072	0.0	2.054	0.0
SPDR	34	2.055	0.3	2.044	0.3
Plano-concave OR	36	2.05(1)	0.17(2)	2.052(6)	0.18(2)
QO	75	2.064	0.0	2.055	0.9
Bi-concave OR	36	2.045	0.2	2.046	0.2

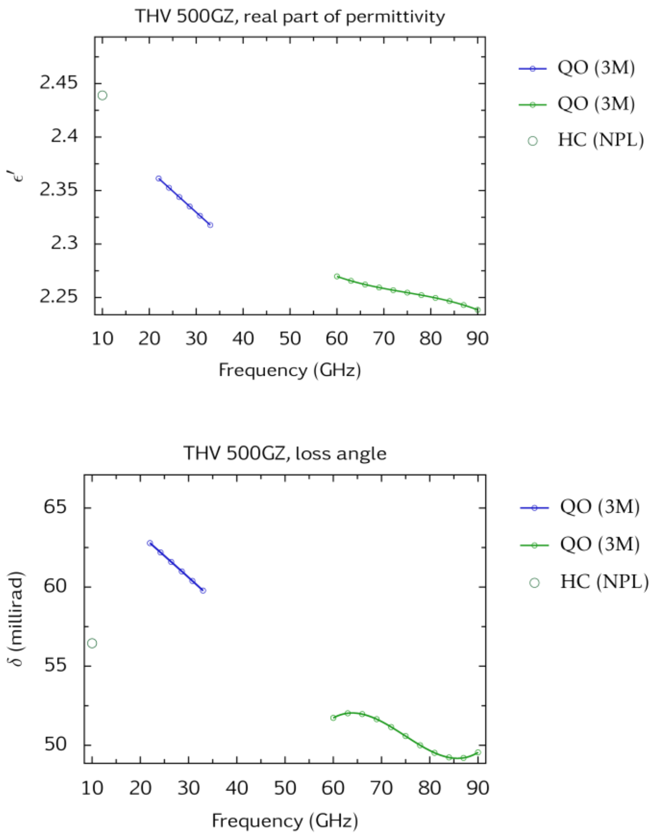


Figure 7: THV 500GZ measurements

Table 2: THV 500GZ measurements

Method	Freq. (GHz)	ε'	δ millirad.
SPDR	9.5	2.43	63
Helical Cav.	10	2.44	56
QO	27	2.34	61
QO	75	2.26	51

$$\Delta\varepsilon' \approx -1.5\,\varepsilon' \tan\delta \log_{10}(f_2/f_1) \qquad (1)$$

For PTFE no significant change in ε′ is expected in the measured range as δ is low valued. For THV 500GZ (δ≈60 milliradians at 10 GHz), ε′ is predicted to fall by approximately 0.2 between 10 GHz and 75 GHz – which is consistent with the results shown in Table 2.

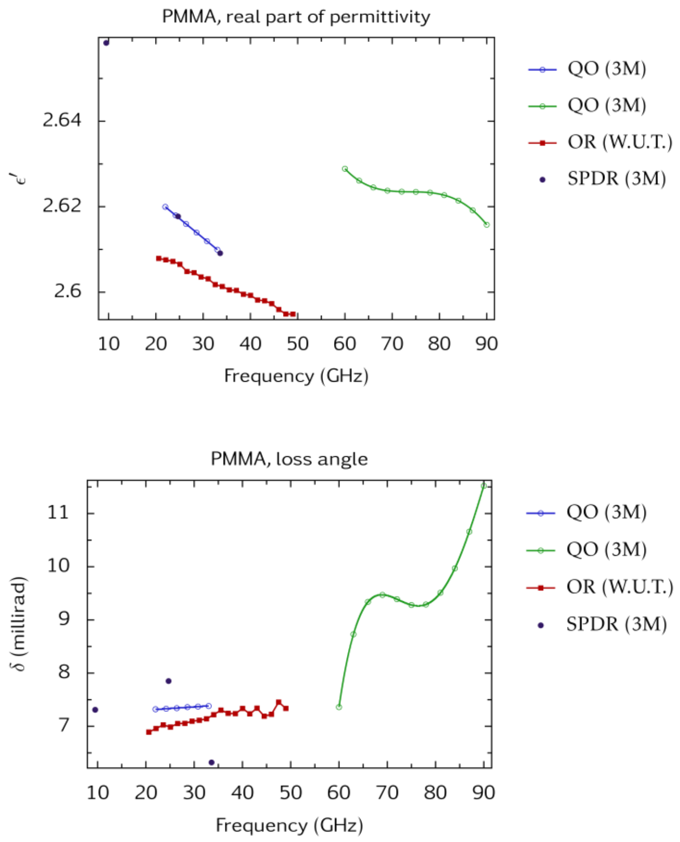
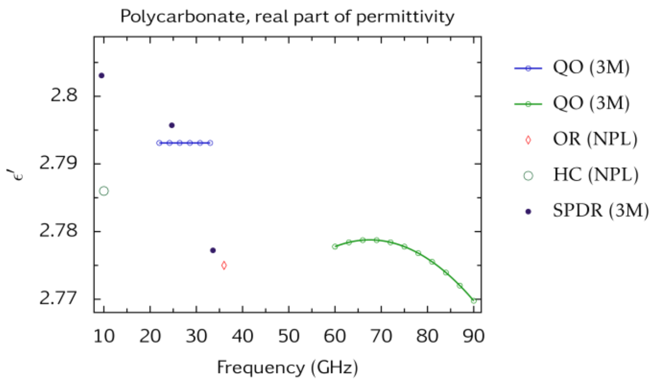


Figure 8: PMMA measurements

Table 3: PMMA measurements

Method	Freq. (GHz)	ε'	δ millirad.
SPDR	9.5	2.66	7
SPDR	25	2.62	8
QO	27	2.62	7
SPDR	34	2.60	6
Bi-concave Open Res.	36	2.60	7
QO	75	2.62	9

The QO transmission methods are not expected to be able to resolve the loss of PTFE. The graphs show that the QO system for the 22 – 33 GHz band is able to resolve the loss for PMMA (7 milliradians), but the 60 – 90 GHz system cannot.



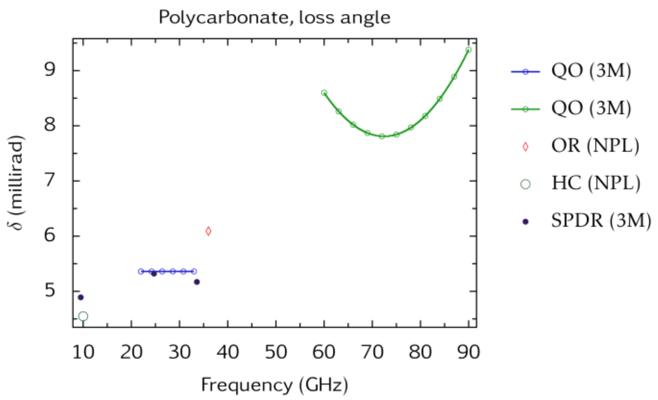


Figure 9: Polycarbonate measurements

Table 4: Polycarbonate measurements.
Bracketed values are uncertainties at coverage factor k=2 (equivalent to approx. 95% confidence level)

Method	Freq. (GHz)	ε′	δ millirad.
SPDR	9.5	2.80	5
Helical Cav.	10	2.79	5
SPDR	25	2.80	5
QO	27	2.79	5
	34	2.78	5
Plano-concave Open Res.	36	2.78(1)	6.0(4)
QO	75	2.78	8

The loss of THV 500GZ was too high to permit measurement by using open resonators. Using the Helical Cavity, a weak resonance with the specimen *in situ* could be detected – although the Q-factor was very low (reduced from 50,000 to 450). The shape of the resonance was poor, which is probably why the measured δ is lower than that obtained with the QO systems.

IV. Conclusion

Specimens of the permittivity and loss angle of four polymers were measured by three resonance methods, and a quasioptic transmission method. Measurements were generally in good agreement. The loss of PTFE is too low to be resolved by the QO systems, but the data is useful as it helps to establish the minimum measurable loss (which is approximately 10 milliradians). The limiting factor is that inserting a specimen causes shifts in the beam waist, which changes the mismatches and coupling (to free space Gaussian beams) at the horns. Resonant methods are complementary to QO methods as they are suitable for measuring low loss materials (typically for loss < 10 milliradians).

Acknowledgment

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