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ORIGINAL PAPER

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Microwave Evaluation of Used-Oil Quality Degradation

Abstract: This paper describes sensitivity of microwaves to the chemical specification variations of an oil fill used in a combustion engine. The evaluation of used oil quality degradation in a combustion engine by measuring the complex dielectric constant (complex permittivity) in the frequency range of X-band (8.5-10.5 GHz) and Ku-band (17.63-18.07 GHz) is investigated. A completely filled short-circuited waveguide technique was used to perform these dielectric measurements. The results have shown that for the frequencies in both X and Ku bands, the dielectric constant and the loss tangent increase as a function of oil usage measured by mileage. The measurements in the X-band give more variation in the complex dielectric constant than the measurements in the Ku-band. It is believed that the oil quality degradation is related not only to the amount of oil usage, but also to the combustion engine state. The analysis procedure as well as experimental results are presented.

Keywords: Microwave, evaluation, energy measurement, used oil, quality degradation

Introduction

Many well-established techniques are available for complex dielectric constant measurement of materials (Bussey 1967). High accuracy and inexpensive microwave measurement techniques have been applied on powders, bulk, and fluid materials for the complex dielectric constant measurements (Bridges *et al.* 1982, Ganchev *et al.* 1994, Zanforlin 1983). Some of the microwave measurement techniques are suitable for materials of low loss ($\tan\delta \angle 0.001$)(Kadaba 1984, Kooi *et al.* 1980).

The chemical properties of many materials are related to the electrical properties. Thus, knowledge of the complex dielectric constant of a specific

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تقييم تدهور خاصية زيت المحرك المستعمل باستخدام الموجات الدقيقة

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المستخلص: يتناول هذا البحث دراسة حساسية الموجات الدقيقة لتغير الخواص الكيميائية لزيت محرك الاحتراق الداخلي وتقييم تدهور هذه الخواص نتيجة لزيادة الاستخدام.إن زيادة استخدام زيت المحرك تؤدي إلى تغير في خواصه الكيميائية، وزيادة تركيز بعض المواد فيه، نتيجة الاحتراق الداخلي المتمثل بزيادة درجة الحرارة والاحتكاك. ومن المواد التي يزداد تركيزها في الزيت نتيجة لزيادة الاستخدام، مادة الكربون، وبما أن الخواص الكهربائية المتمثلة بالسماحيّة أو الكهرنافذية مرتبطة بالخواص الكيميائية لمعظم المواد، فان زيادة نسبة الكربون في الزيت المستعمل تؤدي إلى زيادة في قيمة السماحيّة الكهربائية المركبة (الكهرنافذية المركبة) للزيت، وبالتالي يمكن تقييم تدهور خاصية الزيت من خلال قياس السماحيّة المركبة.

تم في هذا البحث إجراء، تجارب باستخدام تقنية في المجال الترددي – Xوالمجال الترددي–Ku لتقييم كفاءة زيت المحرك المستعمل عن طريق قياس ثابت الكهرنافذية (الجزء الحقيقي لقيمة السماحيّة المركبة) وكذلك قياس ظل الفقد (نسبة الجزء التخيلي لقيمة السماحيّة المركبة إلى الجزء الحقيقي)، وإيجاد علاقة بين هذه القياسات وطول فترة استخدام الزيت، حيث استخدمت تقنية مناسبة للمواد التي لها ظل فقد قليل كمادة الزيت. وقد أثبتت نتائج التجارب العملية في البحث، أن علاقة طول فترة استخدام زيت المحرك مع قيمتي ثابت الكهرنافذية وظل الفقد هي علاقة طرديّة، وحيث إن تدهور خاصية الزيت لا يعتمد على طول الاستخدام فقط بل على كفاءة المحرك أيضاً، فبالتالي أمكن من خلال نتائج التجارب التي أجريت لعينات الزيت المستعملة لمسافات متساوية في محركات ذات نوعيات متشابهة ولكن بأعمار مختلفة من تقييم كفاءة المحرك وإيجاد علاقة بين هذه الكفاءة وقيمة السماحيّة المركبة للزيت المستعمل فيه. علماً أن الزيت المستخدم في تجارب البحث هو زيت محرك ليبي المنشأ صنف (SAE 220W/40).

لقد أعطت نتائج التجارب الخاصة بالقياسات في الحزمة الترددية–X تغيراً في قيمة السماحيّة المركبة للزيت المستعمل أكثر من التغير الذي أعطته القياسات في الحزمة الترددية–Ku نتيجة لزيادة الاستخدام.

تمتاز التقنية المستخدمة في هذا البحث، لتقييم خاصية زيت المحرك المستعمل وكفاءة المحرك تمتاز بأنّ نتائجها دقيقة وقابلة للتكرار، من دون أن يؤثر هذا التكرار على دقة النتائج، واقتصادية إذا ما قورنت بالتقنيات الخاصة بفحص مكونات الزيت كيميائياً وما تحتاج له من عمليات طويلة ومعقدة. مثل التقنيات الخاصة بفحص كفاءة المحرك التي تحتاج إلى أجهزة معقدة، وكذلك تمتاز التقنية المستخدمة، بأنها بسيطة ويمكن إجراؤها بسهولة من قبل الأشخاص الذين ليست لديهم خبرة في هذا المجال.

كلمات مدخلية: زيت المحرك المستعمل–قياس الطاقة.الموجات الدقيقة–تقييم الكفاءه.

sample of used oil may give an indication of the oil quality degradation.

The evaluation technique of quality degradation for an oil fill used in a combustion engine is expensive and it needs a long and complex chemical procedure. Very little is known about the evaluation of quality degradation using microwave techniques.

In this paper, we discuss the results of complex dielectric constant measurements of combustion engine oil fills. To perform this task, oil fills of a four-cylinder petrol engine were used, and many used oil samples having several hundred kilometers of running (100-1400 km) were taken. Also, used oil samples of an equal number of kilometers of running used in similar combustion engine types of different ages were taken. The ability of microwaves to detect the used oil quality degradation for different distances of usage is shown. This type of information may lead to important practical applications such as monitoring and evaluating the state of a combustion engine.

Measurement Procedure

We consider a measurement procedure in a completely filled waveguide with the shorted line technique (Lance 1964) that would possess the following characteristics:

1. be suitable for measuring materials of low loss tangent, like oil (Kraus 1992);
2. be suitable for measuring fluid materials, like oil;
3. be inexpensive , simple, easily assembled, and operated by those who are not trained in this microwave area;

Fig. 1 shows the experimental arrangements used for the waveguide measurement of the dielectric properties of used oil. Two different waveguide set-ups operating in 8.5-10.5 and 17.63-18.07 GHz were used. The oscillator generates a microwave signal at the desired frequency. Instead of using a short circuited waveguide in horizontal position filled with an oil sample applying a piece of clear tape to hold the sample in place (Ganchev *et al.* 1994), a waveguide E-bend can be used to solve this problem. The waveguide E-bend keeps the short circuited waveguide in a vertical position and completely filled by the oil sample. The effect of the E-bend waveguide on the microwave signal can be neglected (Fig. 1).

The electrical properties of a material may be specified by the *complex dielectric constant*(ε). The real and the imaginary parts of this constant are indicated in the following equation:

$$\varepsilon = \varepsilon' - j\varepsilon'' \quad (1)$$

where ε' is the *dielectric constant* and ε'' is the *loss factor.*

A measure of the energy lost in the form of heat is called the *loss tangent* ($\tan\delta$). It is the ratio of the power dissipated to the power stored per cycle, and is given by:

$$\tan\delta = \frac{\varepsilon''}{\varepsilon'} \quad (2)$$

The measurement procedure using the shorted line technique (Lance 1964) includes the following steps:

1. Measuring the wavelength of the shorted waveguide (λ_g)without the dielectric sample.
2. Measuring the 3-dB width ($\Delta\chi$) by the "twice minimum" method (Lance 1964) as indicated in Fig. 2.
3. Recording the position of the minimum (A).
4. Placing the dielectric sample and recording the position of the minimum (B) and then recording the shift in minimum(Δl) .

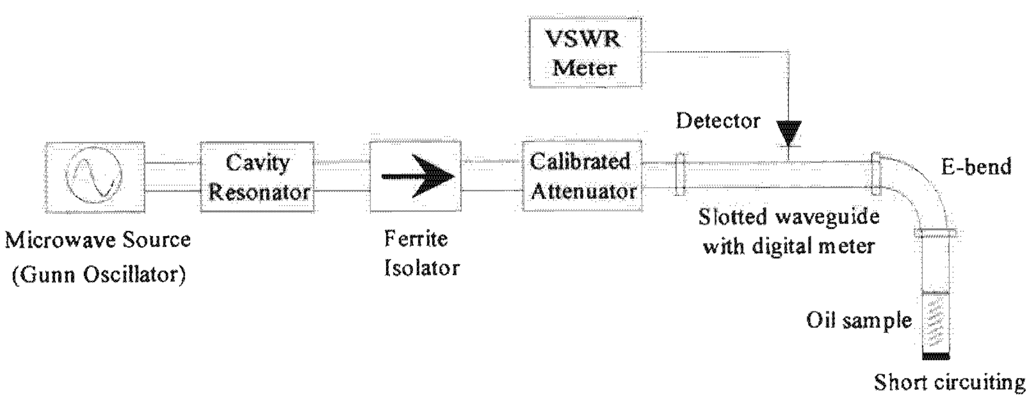


Fig. 1. Experimental arrangement used for the measurement of complex permittivity.

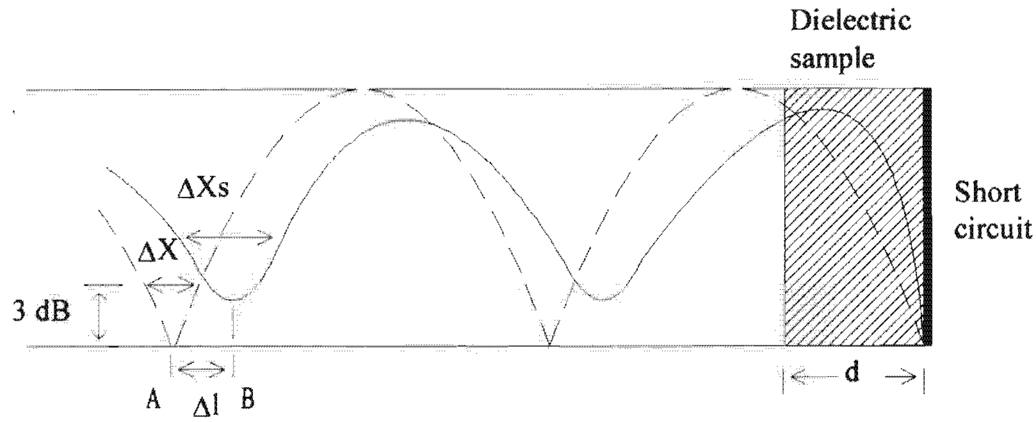


Fig. 2. standing waves in the waveguide with and without sample.

5. Measuring the 3-dB width $(\Delta\chi_s)$ by the "twice minimum" method.

6. Calculating

$$\frac{\tan\chi}{\chi} = \frac{\lambda_g}{2\pi d}\tan\frac{2\pi(\Delta l + d)}{\lambda_g} \quad (3)$$

Theoretically there is an infinite number of x values; an estimated value of the dielectric constant (ε') is needed to solve for x in the preceding equation.

7. Calculating the dielectric constant:

$$\varepsilon' = \left(\frac{\chi\lambda}{2\pi d}\right)^2 + \left(\frac{\lambda}{\lambda_c}\right)^2 \quad (4)$$

8. Calculating the loss tangent:

$$\tan\delta = \frac{\Delta\chi_s - \Delta\chi}{\varepsilon' d}\left(\frac{\lambda}{\lambda_g}\right)^2 \quad (5)$$

To explain the complex dielectric constant calculation procedure and find the correct root of the x values from the estimated value of the dielectric constant, a calculation example (using MathCAD) for an oil fill sample with a thickness of 176-mm and a usage of 1000 km is given in the appendix.

Results and Analysis

In measuring the oil complex dielectric constant, a Libyan engine oil (SAE 20W/40) was used. Many samples of thicknesses 20-260 mm of new (unused) oil were taken to measure their complex permittivity with two different set-ups operating at 9 GHz and 17.9 GHz. Fig. 3 shows the dielectric constant of a new oil fill as a function of the sample width. Fig. 4 shows the loss tangent of a new oil fill as a function of the sample width. Table (1) gives the average values of the dielectric constant and of the loss tangent for the measurements at the two frequencies.

Significantly long oil fill usage changes its chemical properties. This change in the chemical properties means mainly an increase of the carbon content. The carbon content is proportional to the complex dielectric constant (Ganchev *et al.* 1994). In addition, the used oil contains iron particles of a microscopic size originating from the friction between the piston and the cylinder inside the engine.

Fig. 5 shows the dielectric constant for a 176-mm sample width as a function of the oil usage length in km. In Fig. 6 we see the loss tangent for a 176-mm sample width as a function of the oil usage length in km. All the measurements described above were performed with oil fill samples of an engine with 90,000 km of usage length.

Figures 7 and 8 show the dielectric constant and the loss tangent of an oil fill when using a 176-mm sample width and a 1000-km oil fill usage length as a function of the engine age (expressed by the usage length in km). The engines used were of the same type (four-cylinder petrol engines).

As mentioned above, all the measurements described were performed at 9 GHz and 17.9 GHz. The results showed that measurements at 9 GHz give more variations in both the dielectric constant and the loss tangent than measurements at 17.9 GHz (Figs. 3–8; Table 1).

Measurement Accuracy

The accuracy theory of the measurement technique using the short-circuited line method is well established (Chao 1986). The technique used in this paper consisted of measuring the minimum positions (A & B) and the 3-dB (Δx & Δx_S)widths rather than measuring the SWR and the related null position (Ganchev *et al.* 1994), because the SWR values of the oil samples are very high and out of

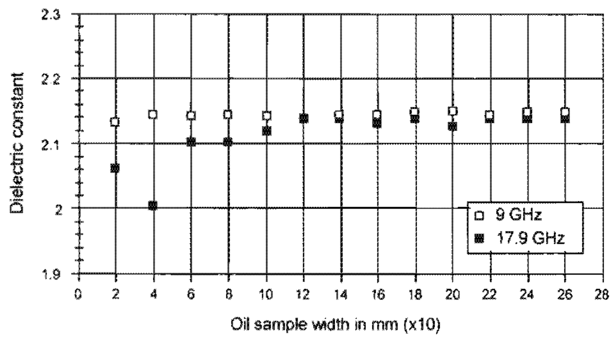


Fig. 3. The dielectric constant (ε′) as a function of new-oil sample width at 9 GHz and 17.9 GHz.

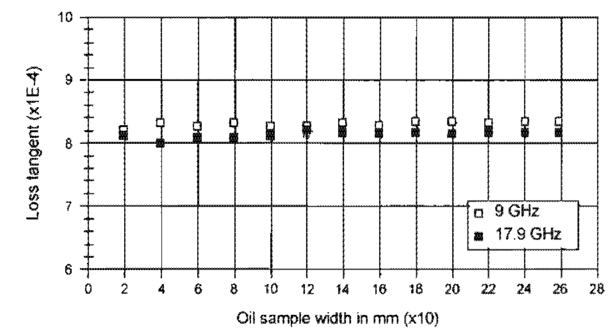


Fig. 4. The dielectric constant (tanδ) as a function of new-oil sample width at 9 GHz and 17.9 GHz.

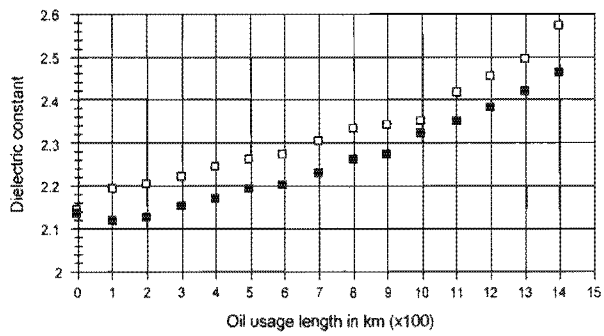


Fig. 5. The dielectric constant (ε′) as a function of the oil fillusage length in km 9 GHz and 17.9 GHz. An oil sample width of 176 mm was used.

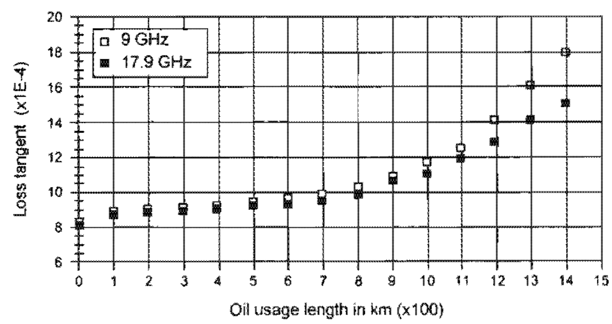


Fig. 6. The loss tangent (tanδ) as a function of the oil fill usage length in km at 9 GHz and 17.9 GHz.An oil sample width of 176 mm was used.

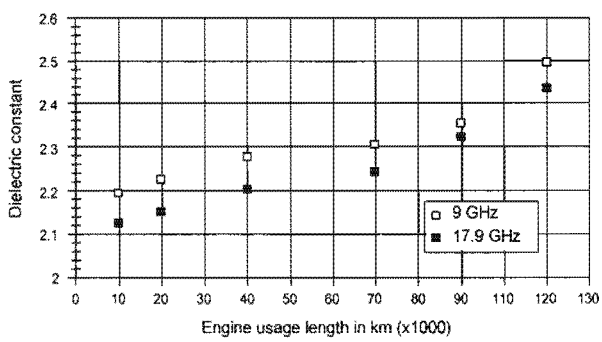


Fig. 7. The dielectric constant (ε′) of an oil fill with 176 mm sample width and 1000 km usage length as a function of engine age (expressed by the usage length in km) at 9 GHz and 17.9 GHz. width at 9 GHz and 17.9 GHz.

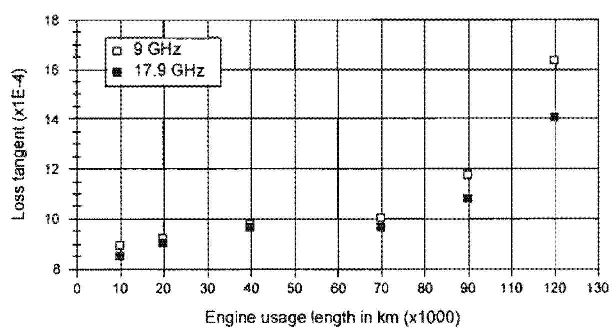


Fig. 8. The loss tangent (tanδ) of an oil fill with 176 mm sample width and 1000 km usage length as a function of engine age (expressed by the usage length in km) at 9 GHz and 17.9 GHz.

Table 1: The average values of both the dielectric constant and the loss tangent for the new (unused) oil fill measurements at 9 GHz and 17.9 GHz.

	Measurement at 9 GHz	Measurement at 17.9 GHz
Average value of the Dielectric constant (ε′)	2.1442	2.1138
Average value of the Loss tangent (tan δ)	0.0008304	0.0008146

SWR-meter range. The 3-dB widths of the standing waves inside the shorted waveguide with and without the dielectric sample are inversely proportional to frequency. Therefore, to improve our measurement accuracy, it is better to measure the complex dielectric constant using a microwave signal in the X-band or even at lower frequencies. A precision dial gauge mounted on the slotted section was used with the waveguide set-up in the X-band, and a digital distance meter mounted on the slotted section was used with the waveguide set-up in the Ku-band in order to obtain precision distance measurements. Also, the accuracy and sensitivity is improved by measuring multiple sample thicknesses for each measurement case.

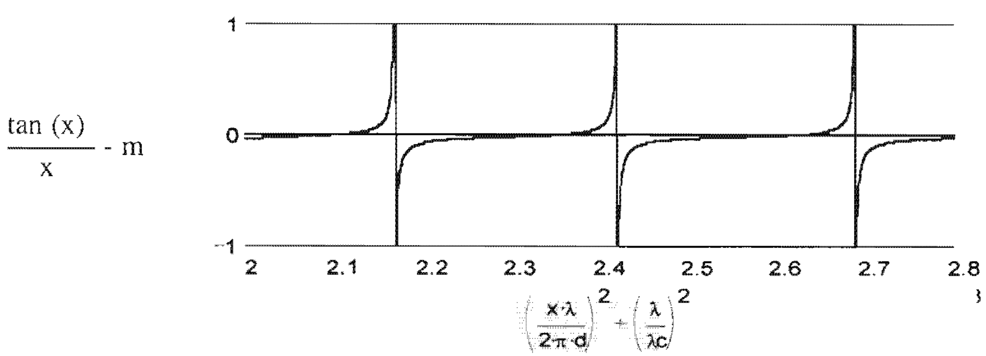
Conclusion

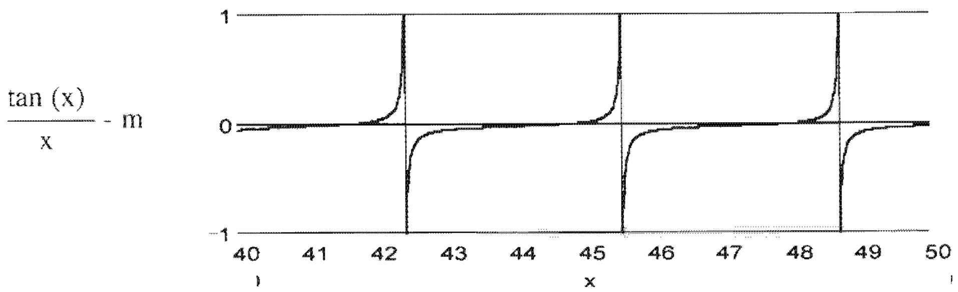
Comparatively simple and inexpensive measurement instrumentation was used to evaluate the quality degradation of a combustion engine oil fill by measuring the complex dielectric constant (complex permittivity). This technique offers good repeatability and measurement accuracy. A good quality Libyan engine oil (SAE 20W/40) was used during the measurements. Two different waveguide set-ups operating in 8.5-10.5 GHz and 17.63-18.07 GHz were used. The measurements of the complex dielectric constant in the frequency range of 8.5-10.5 GHz displayed more variations than the measurement in the frequency range of 17.63-18.07 GHz. Also, the results showed that the increase in both dielectric constant and loss tangent of the measured oil samples is proportional to the increase in the oil quality degradation, which in turn is caused by the increase of usage. The results suggest that the measuring of the oil fill complex dielectric constant may also serve as a means for evaluating the combustion engine state.

Appendix

Calculation Procedure (using MathCad) of the complex dielectric constant oil fill sample with 1000 km of usuage length

Frequency (GHz-):-	$f := 9.0 \cdot 10^{9}$	
Frequency (GHz-):-	$d := 176 \cdot 10^{-3}$	
Shift in the minimum (m):-	$\Delta L := (70.8 - 67) \cdot 10^{-3}$ $\Delta L = 0.0038$	
3-DB width (without the dielectric sample):-	(-m) $\Delta x := .55 \cdot 10^{-3}$	
3-DB width (with the dielectric sample):-	(m) $\Delta xs := 1.4 \cdot 10^{-3}$	
Wavelength width (m):-	$a := 2.28 \cdot 10^{-2}$	
Cutoff wavelength :-	$\lambda c := 2 \cdot a$	
Wavelength :-	$\lambda := \frac{3 \cdot 10^{8}}{f}$	$\lambda = 0.03333$
Measured guide wavelength :-	$\lambda g := (89 - 67) \cdot 2 \cdot 10^{-3}$ $\lambda g = 0.044$	
	$m := \frac{\lambda g}{2 \cdot \pi \cdot d} \cdot \tan\left[2 \cdot \pi \cdot \frac{(\Delta L + d)}{\lambda g}\right]$	$m = 0.02399$
	$x := 40, 40.01 .. 50$	





The estimated value of the dielectric constant:- $\varepsilon 1 := 2.40$

$$x := \frac{2\cdot\pi\cdot d}{\lambda}\cdot\sqrt{\varepsilon 1 - \left(\frac{\lambda}{\lambda c}\right)^2} \qquad x = 45.3136$$

$$t := \mathrm{root}\left(\frac{\tan(x)}{x} - m, x\right) \qquad t = 44.80929$$

$$\varepsilon 1 := \left(\frac{t\cdot\lambda}{2\cdot\pi\cdot d}\right)^2 + \left(\frac{\lambda}{\lambda c}\right)^2$$

$$\tan\delta := \frac{\Delta xs - \Delta x}{\varepsilon 1\cdot d}\cdot\left(\frac{\lambda}{\lambda g}\right)^2$$

$$\varepsilon 2 := \varepsilon 1\cdot\tan\delta$$

Dielectric constant:- $\varepsilon 1 := 2.3587$

Loss tangent:- $\tan\delta = 0.00118$

Loss factor:- $\varepsilon 2 := 0.00277$

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