High Temperature Characteristics of Coplanar Waveguide on R-Plane Sapphire and Alumina

George E. Ponchak, *Fellow IEEE*, Jennifer L. Jordan, *Member IEEE*, and Maximilian C. Scardelletti, *Senior Member, IEEE*

***Abstract*—This paper presents the characteristics of coplanar waveguide transmission lines on R-plane sapphire and alumina over the temperature range of 25 to 400˚ C and the frequency range of 45 MHz to 50 GHz. A Thru-Reflect-Line calibration technique and open circuited terminated stubs are used to extract the attenuation and effective permittivity. It is shown that the effective permittivity of the transmission lines and, therefore, the relative dielectric constant of the two substrates increase linearly with temperature. The attenuation of the coplanar waveguide varies linearly with temperature through 200˚ C, and increases at a greater rate above 200˚ C.**

***Index Terms*—alumina, attenuation, coplanar waveguide, effective permittivity, high temperature, sapphire.**

I. Introduction

THE demand for wireless sensors that operate in harsh environments is increasing. Sensors that operate at high temperatures, from 25 to 650˚ C, are especially in demand for aircraft engine health and performance monitoring, oil drill bit status monitoring, and mining machinery [1], [2]. In addition to these extreme environments, wireless sensors that operate reliably over moderate temperature ranges of 25 to 200˚ C are useful for monitoring electric machinery in industrial environments. The wireless circuitry may rely on transistors based on wide bandgap semiconductors, such as GaN and SiC, that are expected to operate through 600˚ C [3]. One possible substrate for SiC and GaN transistors and circuits is high purity 4-H SiC, which has been shown to be a good, low loss substrate at microwave frequencies through 500˚ C [4], [5]. However, most GaN and SiC transistors have been built on 6-H SiC, and microwave frequency transmission lines on 6-H SiC have been shown to have a very high attenuation constant at high temperatures [6]. GaN transistors may also be fabricated on Sapphire, and GaN contacts on Sapphire have been characterized through 500˚ C [7].

However, GaN or SiC monolithic integrated circuits suitable for high temperature applications are not yet developed. Therefore, hybrid integrated circuits or system on package (SoP) technologies must be used for high temperature. Possible substrates for this application are alumina and Sapphire. For example, a 200˚ C, 1 GHz oscillator [8] and a 400˚ C, 30 MHz wireless sensor [9] have been demonstrated on an alumina substrate using hybrid integrated circuit technologies. Before these circuits can be optimized, the characteristics of transmission lines fabricated on suitable substrates, such as Sapphire and alumina, must be understood over the temperature and frequency range.

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Prior research on the characteristics of alumina and Sapphire as a function of temperature is limited to a few specific frequencies. Alumina has been characterized by a resonant cavity at 2.4 GHz from 25 to 1000˚ C [10]; by refection inside a waveguide at 9.5 GHz from 25 to 1500˚ C [11]; by a dielectric resonator at 8 GHz from 25 to 100˚ C [12]; a coaxial probe at 2.45 GHz from 25 to 800˚ C [13]; and by a dielectric resonator at 2.8 GHz from -100 to 200˚ C [14]. Sapphire was also characterized by [14]; by dielectric resonators at 60 GHz from -50 to 80˚ C [15]; and by coaxial probes from 0.5 to 3 GHz and 600 to 800˚ C [16]. Recently, the authors presented preliminary characteristics of coplanar waveguide on Sapphire as a function of frequency over the temperature range of 25 to 400˚ C [17].

In this paper, we present for the first time the characterization of coplanar waveguide (CPW) on R-plane Sapphire and alumina as a function of frequency, 45 MHz to 50 GHz, and temperature, 25˚ C to 400˚ C. The effective permittivity, ε_{eff}, and attenuation, α, of three different sized CPW lines are extracted by two different measurement methods.

II. Experimental Techniques

Because of the wide temperature and frequency range considered here, two different measurement methods are used to calculate the propagation factor of the CPW lines. The resulting data is compared and shown to be in good agreement. All measurements are made on a specially built RF probe station that permits the wafer chuck temperature to vary from room temperature (25˚ C) to 600˚ C [18]. The wafer chuck is set to the desired temperature and held constant for 10 minutes to allow the substrate to be at a uniform temperature. Measurements are made at 25˚ C, 50˚ C, and in 50˚ C increments through 400˚ C.

A. *Circuit Description and Fabrication*

Three sets of CPW lines are fabricated with center conductor width (S) and slot width (W) of (S,W) equal (40,20), (80,38), and (130,60) with all dimensions in micron. For each CPW, the finite ground plane width is 5S and the characteristic impedance is nominally 50 Ω at room temperature when accounting for metal thickness. The range of strip and slot widths while maintaining a constant characteristic impedance should help to separate effects caused by variations in conductor resistivity and substrate changes in permittivity and resistivity.

Prior to circuit fabrication, all substrates are cleaned using a standard semiconductor process. The R-plane Sapphire is 430 μm thick and polished on both sides. The metal lines are defined by a lift-off process and consist of 0.025 μm of Ti and 1.44 μm of Au. The 508 μm thick, 99.6% alumina is polished on both sides and the metal lines consist of 0.025 μm of Ti and 1.23 μm of Au. All metals are deposited by E-beam evaporation.

B. *Effective Permittivity and Attenuation by TRL Calibration*

A Thru-Reflect-Line (TRL) [19] [20] calibration is performed at each temperature as described in [17]. To improve accuracy as compared to [17], the measurement procedure is repeated on two similar sets of substrates starting at 25˚ C and increasing the temperature to 400˚ C, and the calculated ε_{eff} and α from each set of data is averaged across the frequency band.

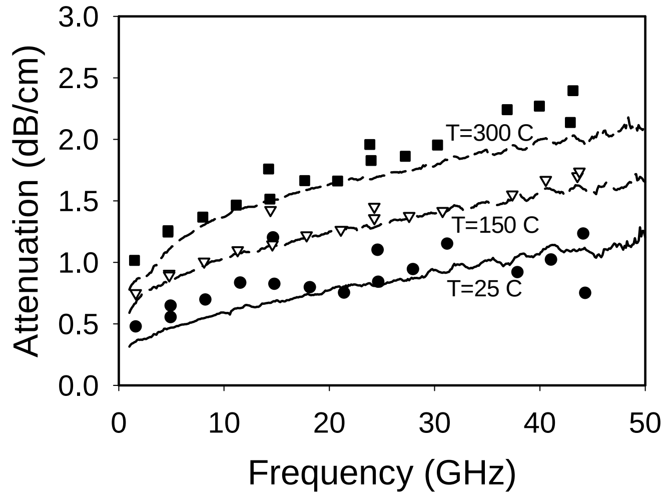
C. *Effective Permittivity and Attenuation by Shunt Stub*

A CPW open circuit terminated shunt stub with the same S and W as the CPW line under investigation is used as described in [17]. Here, two stubs of length 6455 and 19365 μm are used. Since the two stub lengths vary by a factor of three, some of the resonances occur at the same frequency, and the effect of the parasitic reactance may be subtracted. From the resonant frequency and the stub length, ε_{eff} may be calculated [21], [22]. The attenuation may also be calculated from the quality factor, Q, of each resonance and a measurement of $|S_{21}|$ at the resonant frequency [22].

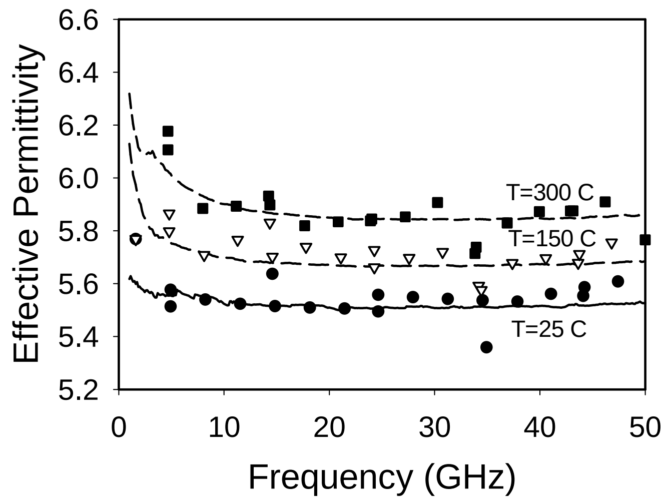
In this paper, the circuits are calibrated using the TRL method with the reference plane set at the T-junction. Stubs are measured for each set of S and W and the measurements are repeated twice. The calculated α and ε_{eff} are averaged at each frequency.

III. Measured Results

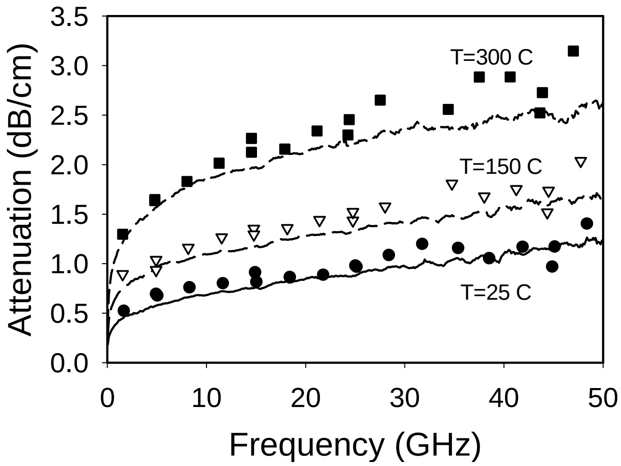
Before analyzing results, first a comparison is made between the α and ε_{eff} determined by both methods. Fig. 1 shows the measured attenuation and effective permittivity for S=80 and W=38 μm CPW lines on Sapphire and alumina. It is seen that the difference between the two methods is less than 10 % for attenuation and 2 % for effective permittivity. It is noted that the determination of α relies on the loaded quality factor of the stub and the magnitude of S_{21} at the resonant frequency. Without the correction factor for $|S_{21}|$, the error is approximately 25% [23]. However, even with the correction factor, the error can be larger than desired because of the inaccuracy in using $|S_{21}|$ at a single frequency, but 10% error reported here does indicate that there is agreement between the two methods. Since the TRL method provides 201 data points across the frequency band as compared to 15 for the shunt stub method, only the TRL method data will be presented throughout the paper.



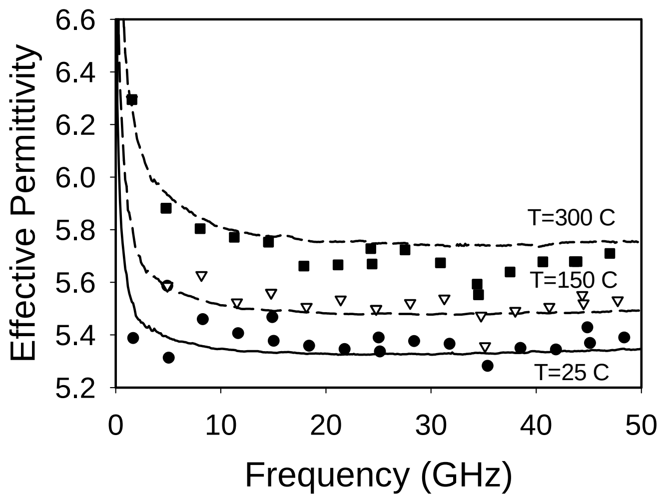
(a) S=80, W=38 μm CPW lines on Sapphire



(b) S=80, W=38 μm CPW lines on Sapphire



(c) S=80, W=38 μm CPW lines on Alumina



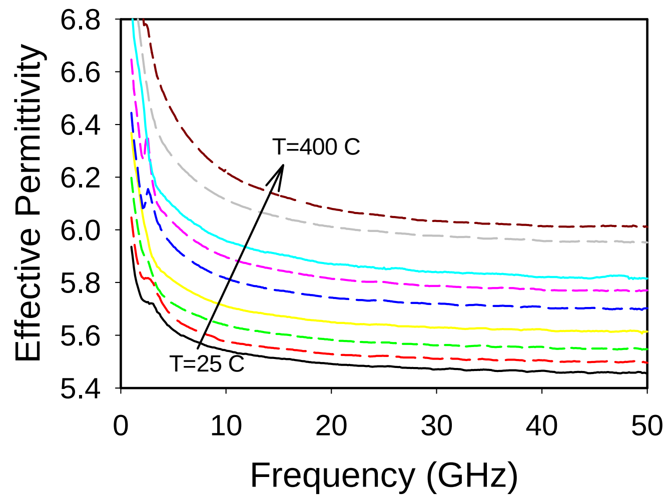
(d) S=80, W=38 μm CPW lines on Alumina

Figure 1: Measured attenuation and effective permittivity as a function of frequency. Lines are TRL method and symbols are Shunt Stub method.

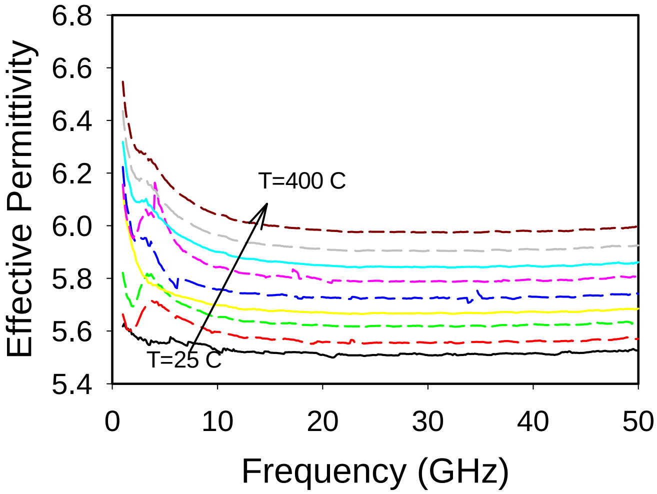
A. *Effective Permittivity*

The measured ε_{eff} for each CPW line is shown in Fig. 2. Ignoring the small perturbations at low frequency, which are due to measurement uncertainties caused by using delay lines that are too short, it is seen that ε_{eff} decreases with frequency until a minimum point and then flattens out and slowly increases with frequency. This response is commonly seen for thin film, microwave transmission lines, and the low frequency response is due to the increased loss caused by the thin metal while the high frequency response is due to a higher concentration of electric fields in the substrate. Note that this characteristic is not temperature dependent. It is also seen that ε_{eff} increases with temperature smoothly across the frequency range.

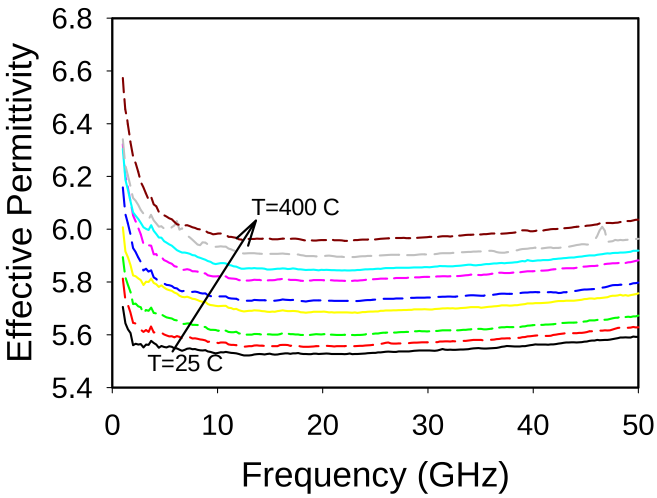
At the minimum point in ε_{eff}, the value measured should be close to the quasi-static value expected by theory, which for CPW is $\varepsilon_{eff}=(\varepsilon_r+1)/2$ where ε_r is the relative dielectric constant. It is noted that the quasi-static value for ε_{eff} is not dependent on the CPW geometry. In fact, even to a second order approximation that accounts for the substrate thickness and frequency, ε_{eff} does not vary with S and W [23]. Thus, in Fig. 3, ε_{eff} at 25 GHz for each CPW line on Sapphire and alumina is plotted. It is seen that ε_{eff} increases linearly with temperature for both substrates. For Sapphire, $\varepsilon_{eff}=5.48\cdot(1+2.26\cdot10^{-4}\ T)$ and for alumina, $\varepsilon_{eff}=5.287\cdot(1+2.57\cdot10^{-4}\ T)$ for T≥0˚ C. Through the use of the quasi-static equation for ε_{eff}, the relative dielectric constant for each substrate may be approximated, resulting in $\varepsilon_r=9.96\cdot(1+2.49\cdot10^{-4}\ T)$ for Sapphire and $\varepsilon_r=9.57\cdot(1+2.84\cdot10^{-4}\ T)$ for alumina for T≥0˚ C. The room temperature value of ε_r for Sapphire of 10.02 compares well with the values of 10.06 [25] and 9.42 [15] reported in the literature, but the Temperature Coefficient of permittivity (TCε) of $2.49\cdot10^{-4}$/°C is approximately three times the TCε of $0.86\cdot10^{-4}$/°C reported in [15]. The room temperature value of ε_r for alumina of 9.64 compares well with value of 9.687 [12], but the TCε of $2.84\cdot10^{-4}$/°C is approximately three times the value of $1.11\cdot10^{-4}$/°C reported in [12], [14]. The higher TCε reported here is caused by the increased attenuation of the CPW lines with temperature due to decreased resistivity of the substrate and increased resistivity of the metal CPW structures with temperature, which increases the propagation constant or ε_{eff} [26]. Unfortunately, the method used here to determine ε_{eff} cannot separate the effects of increased loss from changes in ε_r.



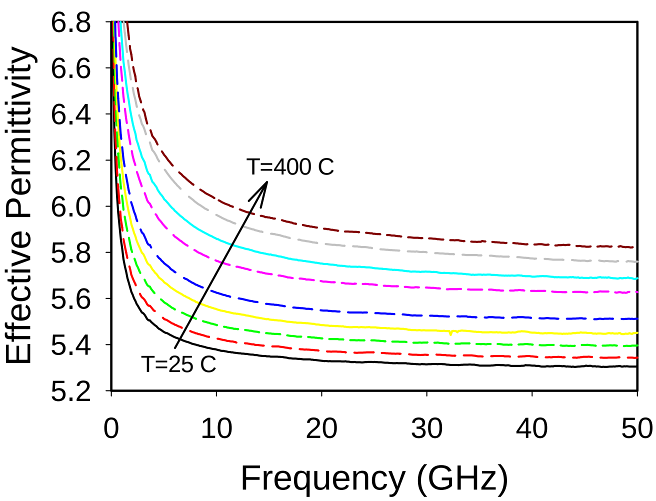
(a) S=40, W=20 μm CPW lines on Sapphire



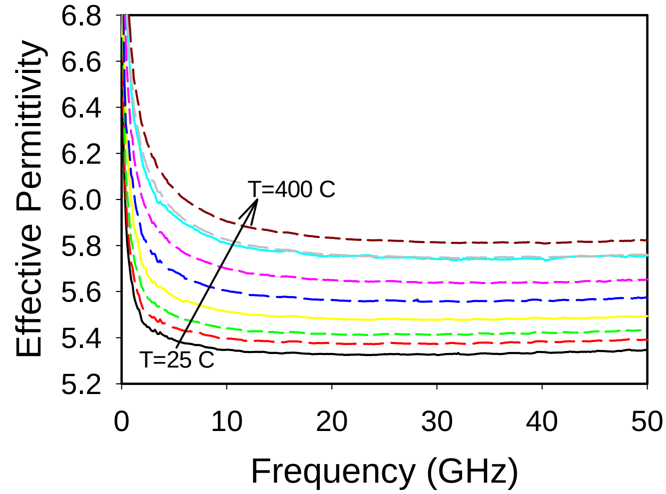
(b) S=80, W=38 μm CPW lines on Sapphire



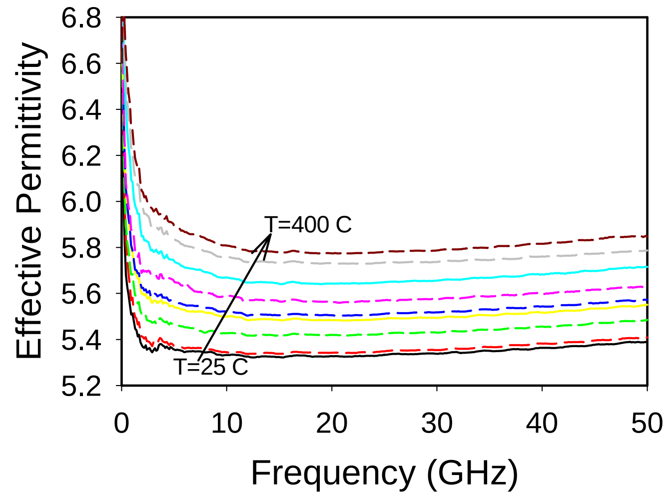
(c) S=130, W=60 μm CPW lines on Sapphire



(d) S=40, W=20 μm CPW lines on Alumina

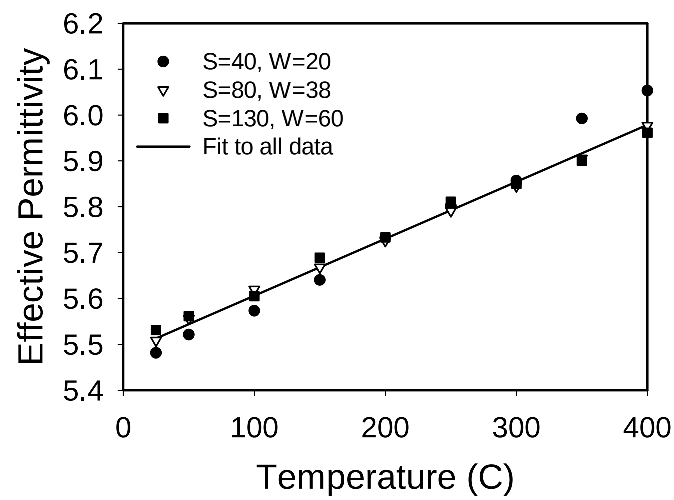


(e) S=80, W=38 μm CPW lines on Alumina

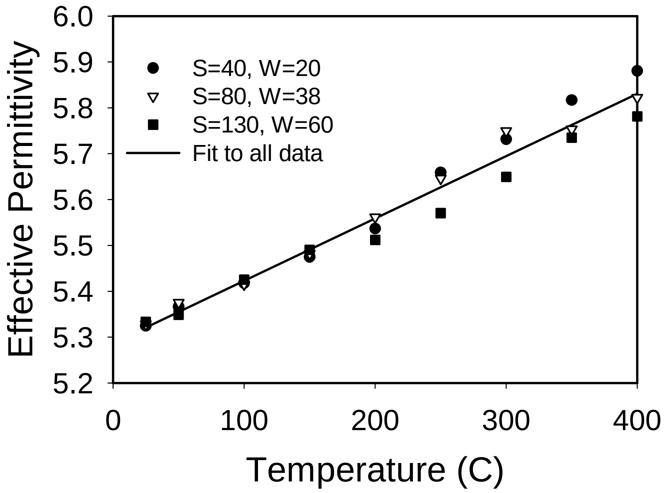


(f) S=130, W=60 μm CPW lines on Alumina

Figure 2: Measured effective permittivity as a function of frequency and temperature for CPW lines of different dimensions on Sapphire and Alumina. Temperatures are 25, 50, 100, 150, 200, 250, 300, 350 and 400° C.



(a) CPW lines on Sapphire



(b) CPW lines on Alumina

Figure 3: Measured effective permittivity as a function of temperature at 25 GHz.

B. Attenuation

The measured attenuation as a function of frequency for each substrate and CPW line width is shown in Fig. 4. First, it is noted that attenuation increases with frequency and temperature smoothly for all of the CPW lines on both substrates, with no data sets being excluded because of results that fall outside of the trend lines (See Fig. 5). Second, although not apparent by observation, the attenuation does not increase as the $f^{0.5}$ as expected if conductor loss were the only loss mechanism. By fitting each curve to $\alpha=y_0+af^b$, it is found that a increases with increasing temperature and decreasing CPW dimensions as expected, but b decreases from approximately 0.6 to 0.25 as temperature increases from 25 to 400° C.

Fig. 5 shows the measured attenuation as a function of temperature at three frequencies, 5 GHz, 25 GHz, and 50 GHz, which may be considered as low, intermediate, and high frequency. These designations are based on the metal thickness, t, relative to the skin depth, δ, which is 1.3, 2.8, and 4 for 5, 25, and 50 GHz, respectively, at room temperature for the CPW lines characterized. Usually, t/δ=3 is assumed as the boundary for thick metal approximations. The attenuation due to conductor loss may be approximated as $R_s/(2Z_c)$ where R_s is the metal surface resistance and Z_c is the characteristic impedance of the line [26]. The metal resistivity is given in [27], resulting in:

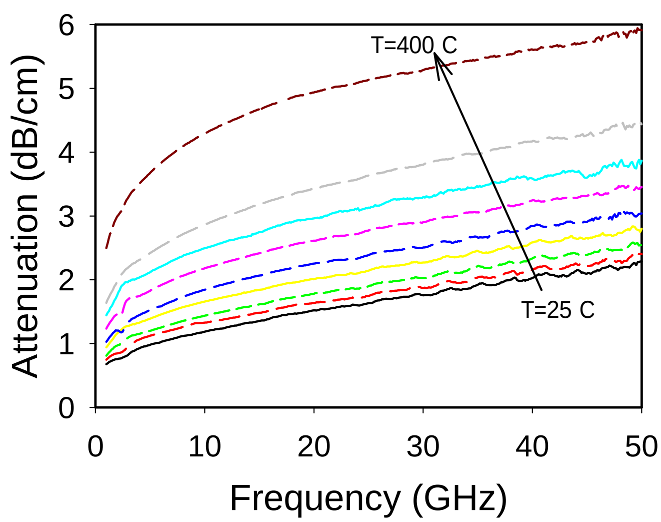
$$\alpha = P\left[\frac{\rho/\delta}{1-e^{-t/\delta}}\right] \qquad (1)$$

where P is a geometry dependent parameter that is related to Z_c. The resistivity, ρ, may be approximated as $\rho=\rho_t(1+\alpha_t T)$ [28] over a small range of temperature. Using this definition of ρ in (1) and the first two terms of the Taylor series expansion of $\rho^{0.5}$ for t/δ>>1, which is accurate for temperature less than 200° C, α is:

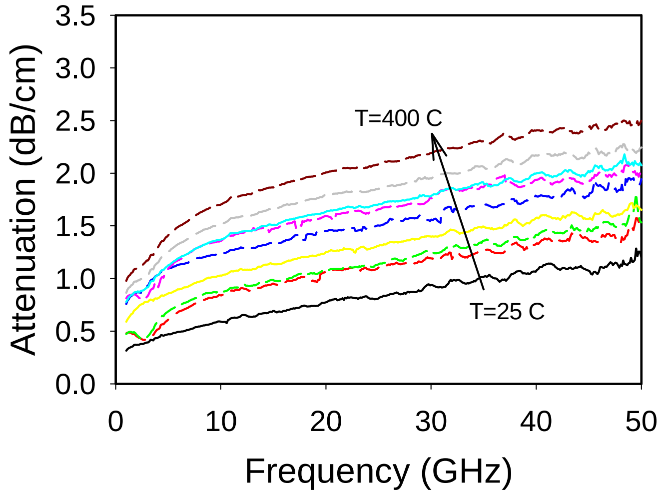
$$\begin{aligned} \alpha &= \frac{P\ \rho_t}{t}(1+\alpha_t T), \quad t/\delta << 1 \\ \alpha &= \frac{P\rho_t}{\delta}(1+\frac{\alpha_t T}{2}), \quad t/\delta >> 1 \end{aligned} \qquad (2)$$

where δ is the skin depth for $\rho=\rho_t$.

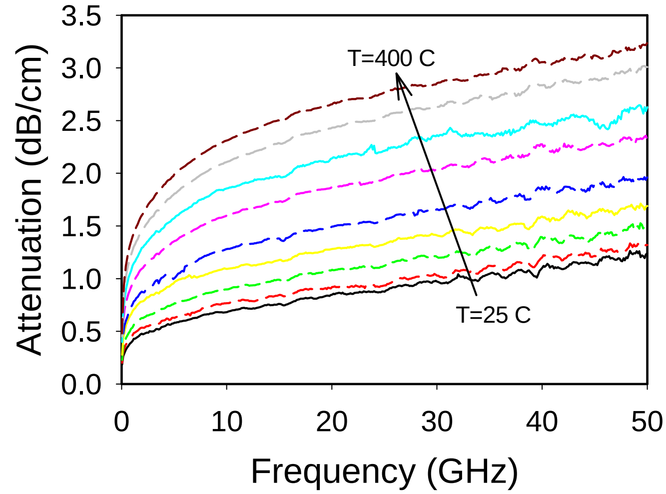
Based on (2), it is seen that for T<200° C, α should increase linearly at low and high frequencies, and this is verified in Fig. 5 where a straight line fit to the data is shown. At higher temperatures, the linear increase in resistivity with temperature and the Taylor series expansions must be changed to include second order terms to account for the increased rate of attenuation with temperature. However, even then, the attenuation predicted by (1) does not accurately explain Fig. 5 because the decrease in substrate resistivity with temperature has not been included. It is seen in Fig. 5, that the variation of attenuation with T is dependent on the CPW line widths, which is the term P in (1) and (2). It is also seen that, especially for the lines on Sapphire, the variation with T becomes more linear throughout the entire temperature range as the line widths are increased. Whether this is due to a canceling of the higher order conductor loss terms and the dielectric loss terms or if this is an artifact of the measurements is not known.



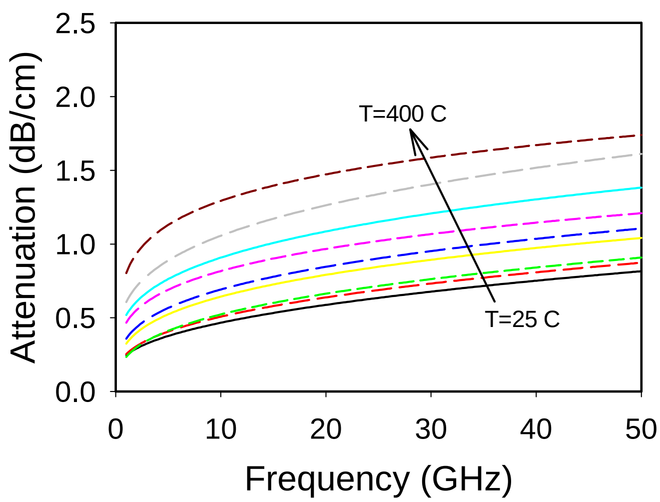
(a) S=40, W=20 μm CPW lines on Sapphire



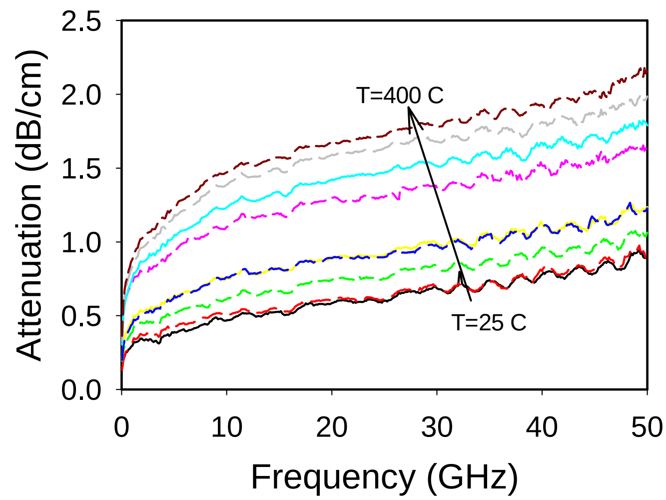
(b) S=80, W=38 μm CPW lines on Sapphire



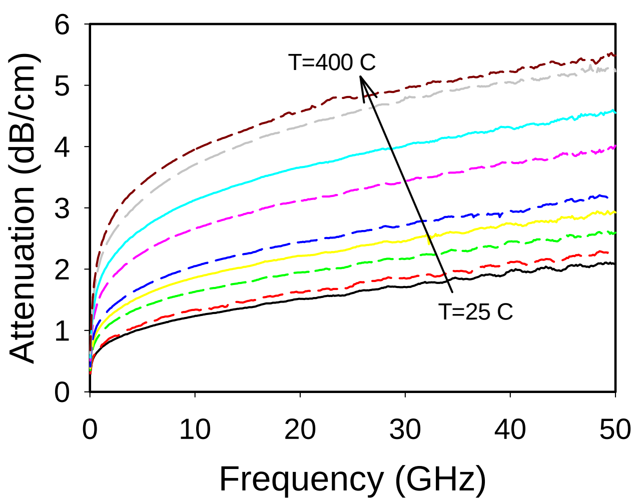
(e) S=80, W=38 μm CPW lines on Alumina



(c) S=130, W=60 μm CPW lines on Sapphire

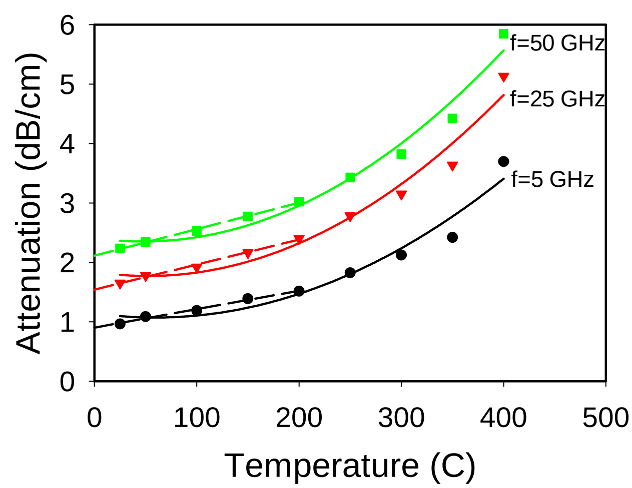


(f) S=130, W=60 μm CPW lines on Alumina

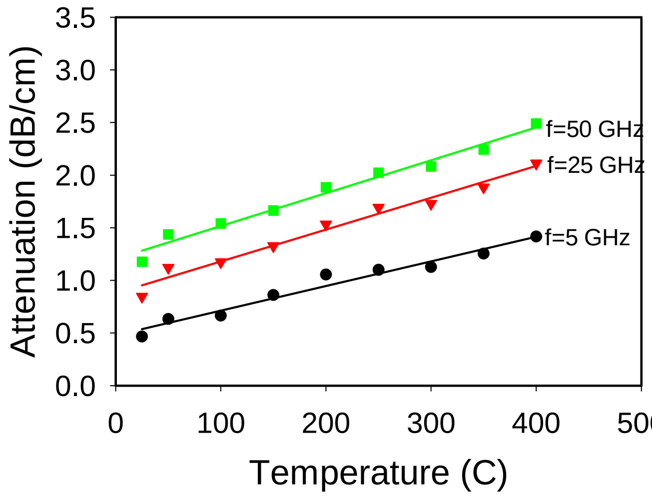


(d) S=40, W=20 μm CPW lines on Alumina

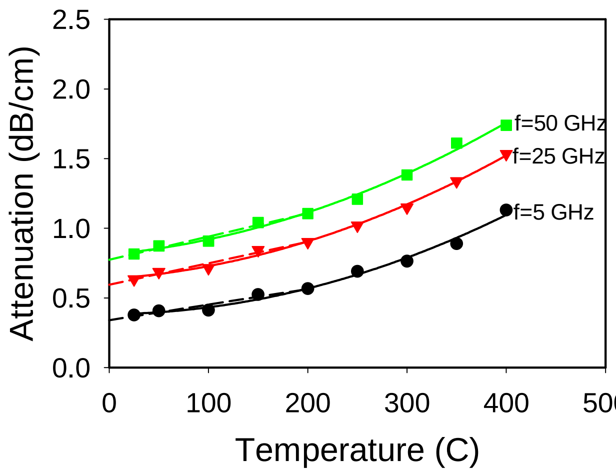
Figure 4: Measured attenuation as a function of frequency and temperature for CPW lines of different dimensions on Sapphire and Alumina. Temperatures are 25, 50, 100, 150, 200, 250, 300, 350 and 400° C.



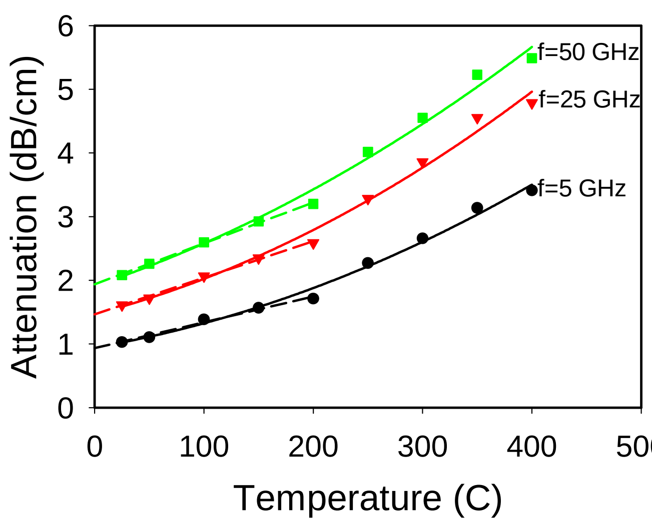
(a) S=40, W=20 μm CPW lines on Sapphire



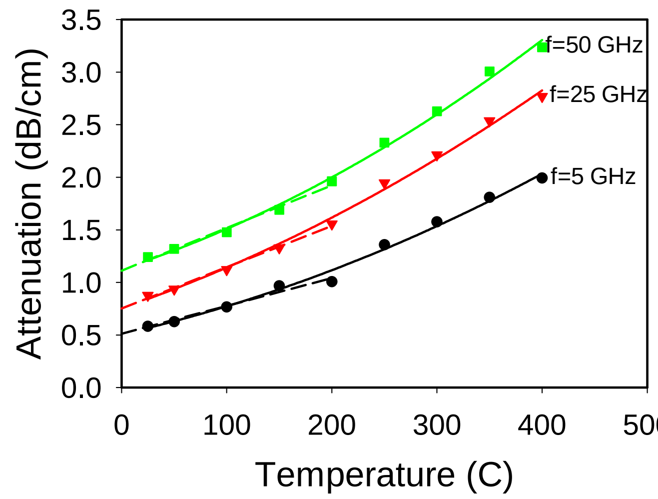
(b) S=80, W=38 μm CPW lines on Sapphire



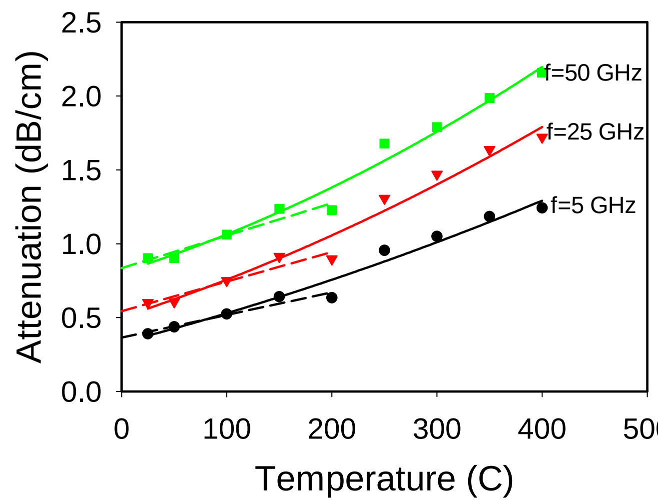
(c) S=130, W=60 μm CPW lines on Sapphire



(d) S=40, W=20 μm CPW lines on Alumina



(e) S=80, W=38 μm CPW lines on Alumina



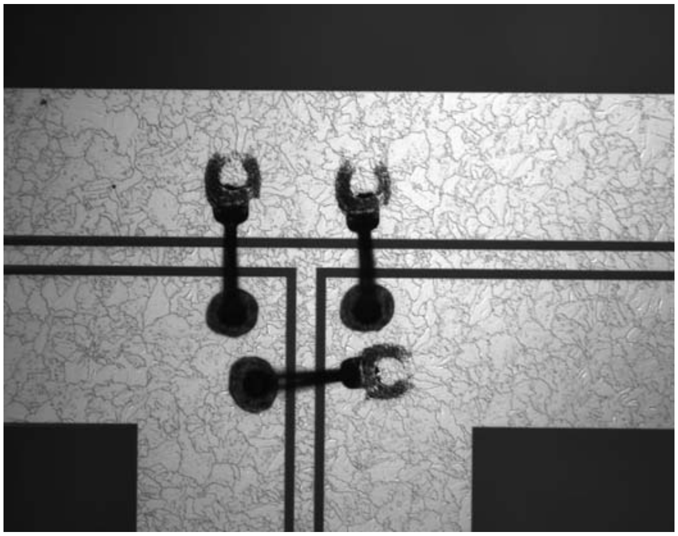
(f) S=130, W=60 μm CPW lines on Alumina

Figure 5: Measured attenuation versus temperature for CPW lines on Sapphire and alumina. Smooth curves are fit to all data and dashed lines are fit to data ≤200 C.

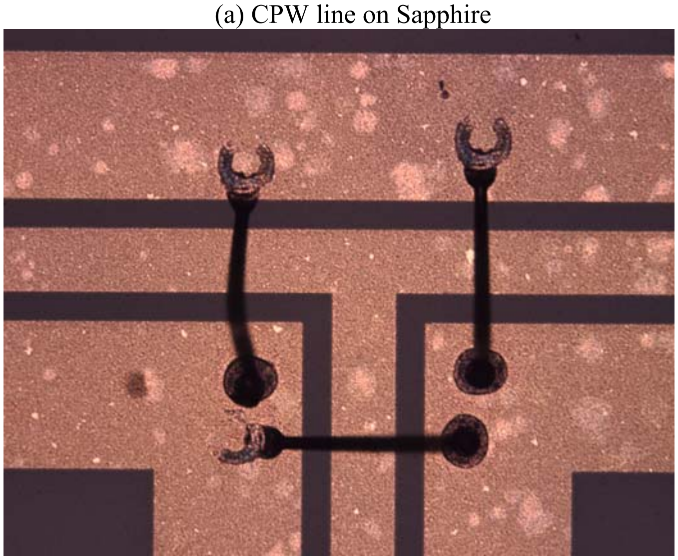
IV. Discussion

The effective permittivity and the temperature coefficient of permittivity for alumina and sapphire are very similar, thus, the size of circuits on both substrates are similar. Furthermore, the attenuation of transmission lines on both substrates is similar, thus, low loss circuits may be built on either substrate. Therefore, based solely on electrical characteristics, either substrate may be used for high temperature SoP circuits. However, there are differences in the mechanical characteristics of metal lines deposited on the two substrates.

The characteristics reported are for CPW lines deposited onto a substrate with the bottom of the substrate resting on a ceramic heater at the test temperature. The Ti/Au metal on alumina did not show any degradation after heating to 400˚ C, and in fact some samples were characterized several times. However, the metal lines on Sapphire showed cracking after heating to 200˚ C, and the cracking was severe looking after heating to 400˚ C. After heating to 300˚ C, the Sapphire samples could be characterized again, and the attenuation was comparable to the before heated data, but after 300˚ C, the attenuation was higher by approximately a factor of 2. Fig. 6 shows a photograph of the CPW lines of each sample after heating to 400˚ C. Therefore, Ti/Au metal transmission lines on Sapphire are not suitable for high temperature SoP circuits.



(a) CPW line on Sapphire



(b) CPW line on Alumina

Figure 6: Photograph of CPW lines on Sapphire and alumina after heating to 400˚ C.

V. Conclusion

Microwave transmission lines on Sapphire and alumina characterized as a function of temperature and frequency have characteristics that are acceptable for high temperature circuit design. The effective permittivity increases linearly by approximately the same amount of 10 % over the temperature range of 375˚ C, but the variation is smooth. The attenuation increases by a factor of 2 to 3 for the CPW lines measured, and this increase will affect system performance since transistor performance decreases with increasing temperature. Because of the metal degradation after 400˚ C heating, alumina appears to be the better substrate for high temperature system on package applications.

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