Characterization of Insertion Loss of Striplines on Various Substrate Materials as a Function of Temperature

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***Abstract*— When designing circuit boards or packages for automotive or military applications, we are concerned with the insertion loss of the transmission lines on various substrate materials over a wide range of temperature. For signal integrity engineers, this affects the maximum length of the transmission line allowed. It is relatively straightforward to simulate the insertion loss at room temperatures. It is not so easy to figure out the insertion loss at high temperatures without significant investment of time and money. In this paper, the metrology of the temperature impact on the transmission line loss was proposed and the relative increase in measured insertion loss of striplines on various substrate materials were shown due to increase in temperature. We broadly categorized the materials as standard loss, mid loss, low loss and ultra low-loss. It is hoped that this data will be useful for engineers to estimate the insertion losses of their transmission lines at high temperatures.**

Keywords*— *dielectric losses; dielectric substrates; signal integrity; temperature dependence; transmission line measurements

I. Introduction

Signal integrity engineers regularly need to determine what the maximum length of the traces that can be routed on the board is. The insertion loss due to the traces is usually determined at room temperatures, as that is the temperature the loss tangent (and dielectric constant) of the dielectric material is usually available at. The engineer would then need to estimate the worst cases losses at the high temperature end of the application. (The thermal engineer can simulate a temperature distribution map of the circuit board.) With available data, the losses at the high temperature end can be estimated more accurately, especially for critical applications in the military and automotive space.

Previous work on characterizing the temperature dependence of insertion losses focused on ultrasonic [1] [2] or fiber optic [3] applications. There has been some research on the effect of frequency and temperature on the dielectric properties of thin films [4]. There is little published research on characterizing the effects of temperature and frequency on the losses of common printed board materials. In this paper, the focus is on characterizing the temperature dependence of transmission line insertion losses on printed circuit boards. We will present data from the characterization so that the engineer can estimate board losses at high temperatures more easily.

Section II will examine the methodology of the characterization. Section III will look at the results of the characterization.

II. Methodology

A. Equipment and Configuration

The testing setup in Fig. 1 requires a temperature chamber, a vector network analyzer (VNA), a test board and test cables.

The VNA used was a Keysight 5071C. The test board had 2 differential striplines, one was 10 inches long and the other 5 inches long. The striplines were 4 mils wide with 7 mils spacing. Delta-L de-embedding methodology [5-7] was adopted for the de-embedding. The device under test (DUT) in Fig. 2 is designed with the coaxial connector for the robust and accurate characterization. Test cabling that is resistant to high temperature is preferred for this temperature cycle experiment.

B. Testing Procedure

1) Prerequisites for testing

A room temperature measurement should be done to see if the insertion losses on the striplines are within expected values. It is desirable that the length of each cable inside the chamber be the same. The length of each cable outside the chamber should be the same too. The Delta-L de-embedding should mitigate the temperature impact of the cable.

The test board should be preconditioned to have consistent characteristics, as loss measurements are very sensitive to moisture. Preconditioning involves keeping the test board at 23 ± 2 °C and 40 ± 5% relative humidity for at least 48 hours.

Fig. 1. Testing Setup

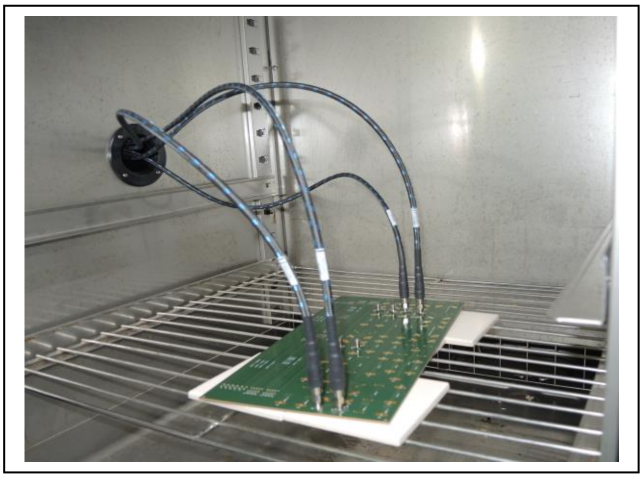

Fig. 2. Device under test in the chamber

2) Testing configuration

The insertion loss measurements are taken at 7 temperature points: 0 °C to 120 °C in steps of 20 °C. We start from 0 °C and move to the higher temperatures. When the chamber reaches the testing temperature, it is good to ensure DUT in this temperature point for half an hour before taking the measurement to ensure that the test board has reached the testing temperature. During the insertion loss measurements, the humidity of the chamber is kept at 50 ± 5% at each temperature point, except at 0 °C, 100 °C and 120 °C.

The intermediate frequency (IF) bandwidth in VNA setup is set to 1 kHz for proper measurement quality. The frequency range is 10 MHz to 20 GHz and the number of sampling points is 2000.

3) Testing procedure

The test procedure is addressed in the following.

a) Set the VNA to settings described in the testing configuration.

b) Calibrate to the SMA connectors of the cables.

c) Set chamber to the lowest testing temperature. (0 °C)

d) Set the chamber to the correct humidity if the temperature is 20 to 80 °C.

e) Wait half an hour for test board to be at the testing temperature.

f) Take the insertion loss measurement and save the data.

g) If the temperature is not the highest temperature required, increase the chamber temperature to the new temperature and go to step (e).

h) Measure the 5 inch trace in the same way.

i) Post-process the data with the Delta-L de-embedding method.

III. RESULTS

There are 27 materials in this characterization work and these are divided into 4 groups based on their insertion losses at room temperature at 4 GHz. The categories are:

- Standard loss: > 0.7 dB/in
- Mid loss: 0.55 dB/in to 0.7 dB/in
- Low loss: 0.40 dB/in to 0.55 dB/in
- Ultra-low loss: < 0.4 dB/in

Only 1 material measured classified as standard.

A. Relative Loss Increase for Various Material Loss Categories

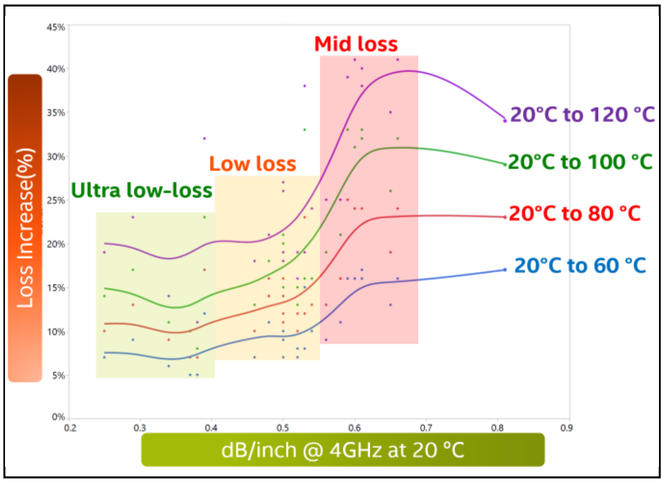

Fig. 3. Percentage loss increase with temperature for various materials

Fig. 3 shows the relative loss increase vs. losses at room temperature. **The relative loss increase is the relative increase in the dB value per inch, compared with the base line loss at 20 degrees.** Each dot represents one material property and these lines are the least mean square fit of these data for the various temperature increases. When the temperature increases, the loss increases accordingly and different material properties are much different. Lower loss materials are less sensitive to temperature increase since low loss resins have more stable electrical properties when the operating environment temperature is increasing.

TABLE I shows the minimum, mean and maximum percentage increase in losses at 4 GHz for these various material loss categories. The maximum values can be used to compute the worst case estimate for the maximum trace lengths on the boards for a given material and a given maximum temperature. Different materials have different temperature sensitive characteristics. The material with less loss characteristics is less sensitive to the temperature change. According to the thermal distribution, PCB temperature are different in different areas and designers can fully utilize this experimental data to estimate the total loss with different routing lengths by temperature impact.

TABLE I. PERCENTAGE LOSS INCREASE AT 4 GHZ FOR VARIOUS MATERIAL LOSS CATEGORIES

Temperature Increase (°C)	Type	Ultra Low Loss	Low Loss	Mid-Loss	Std.[a] Loss
20 to 60	Min.	5%	7%	9%	
	Mean	7%	10%	14%	17%
	Max.	12%	15%	17%	
20 to 80	Min.	7%	10%	13%	
	Mean	11%	14%	21%	23%
	Max.	17%	23%	25%	
20 to 100	Min.	8%	13%	19%	
	Mean	14%	18%	28%	29%
	Max.	23%	33%	33%	
20 to 120	Min.	11%	16%	25%	
	Mean	20%	22%	36%	34%
	Max.	32%	38%	41%	

[a] Only 1 standard loss material was measured, so there is no min. or max value.

B. Relative Loss Increase for Different Frequencies

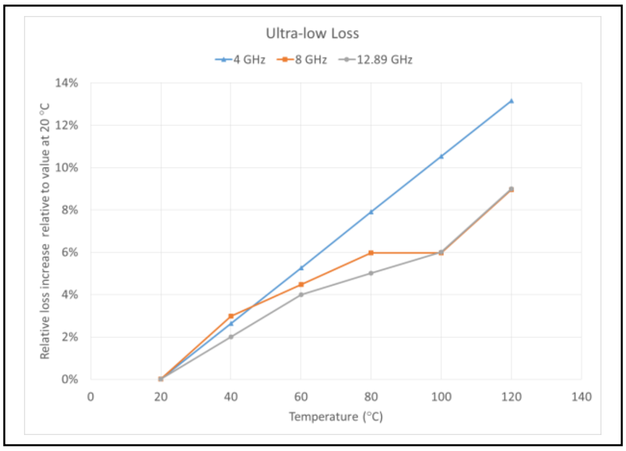

Fig. 4. Percentage loss increase with temperature for different frequencies for an ultra-low loss material

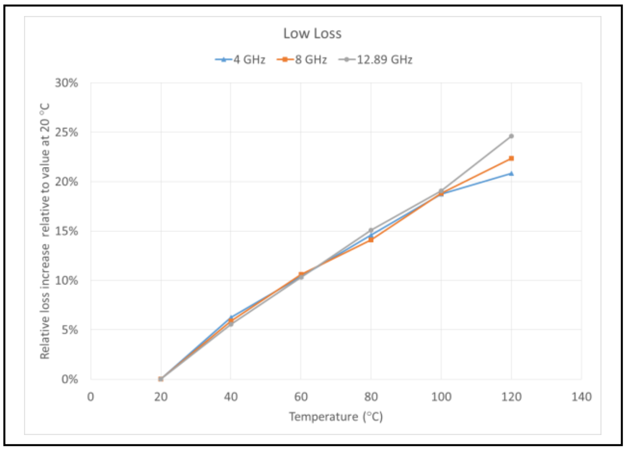

Fig. 5. Percentage loss increase with temperature for different frequencies for a low loss material

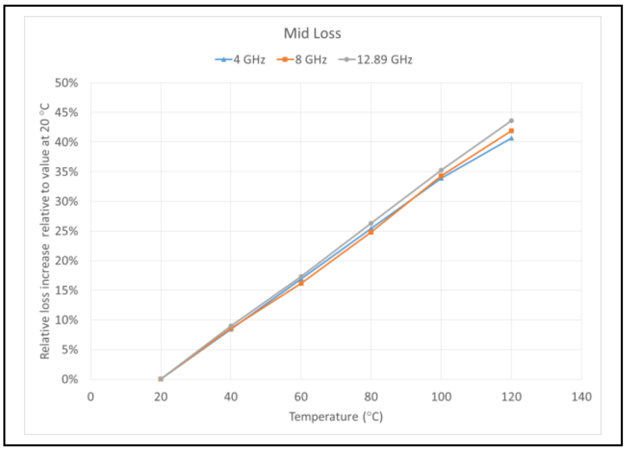

Fig. 6. Percentage loss increase with temperature for different frequencies for a mid loss material

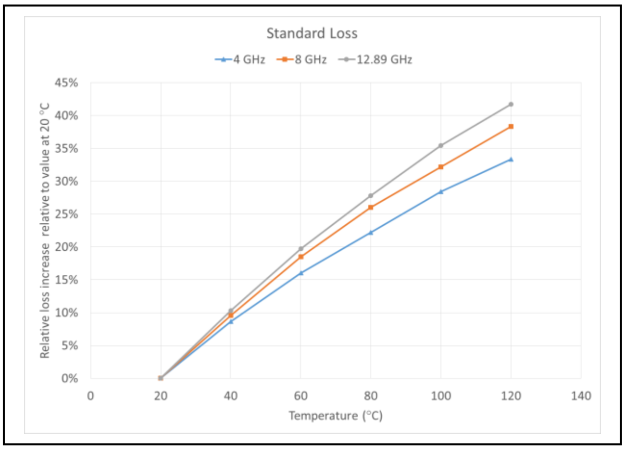

Fig. 7. Percentage loss increase with temperature for different frequencies for a standard loss material

Fig. 4 to Fig. 7 show the percentage loss increase with temperature for 1 type from each of the 4 material categories at 3 frequencies: 4 GHz, 8 GHz and 12.89 GHz. The graphs show that the percentage increase is mostly linear with temperature, with the lower loss material giving less relative increase than the higher loss material. The linear increase agrees with previous published results (see Fig. 5 and Fig. 6 in [4]). These graphs can be used along with Table I. to estimate the losses up to 120 °C and frequencies up to 12 GHz.

IV. Conclusion

In this paper, the temperature impact metrology was proposed as an industry reference and we have characterized the temperature dependence of the insertion losses on various printed circuit board materials. Different materials have different temperature sensitive characteristics and the material with less loss characteristics is less sensitive to the temperature change. The data in this paper can be used by engineers trying to estimate the maximum trace lengths for their high speed I/O interconnect.

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References

[1] A. E. Meitzler, “Temperature and frequency dependence of insertion loss in delay lines,” IRE National Convention, pp. 153-160, Mar. 1958.

[2] R. S. Falconer, J. F. Vetelino and B. H. T. Chai, “Infrared measurements, temperature coefficient of delay and insertion loss of heat treated berlinite samples,” IEEE Ultrasonics Symposium, pp. 241-246, Oct. 1985.

[3] L. McCaughan and E. J. Murphy, “Influence of temperature and initial titanium dimensions of Fiber-Ti: LiNbO3 waveguide insertion loss at l = 1.3 um, IEEE Jour. Quantum Electronics, vol. 19, pp. 131-135, Feb. 1983.

[4] V. S. Yadav, D. K. Sahu, Y. Singh and D. C. Dhubkarya, “The effect of frequency and temperature on dielectric properties of pure poly vinylidene fluoride (PVDF) thin films,” Proc. IMECS 2010, vol. III, Hong Kong, Mar. 2010.

[5] “Intel Delta-L methodology for electrical characterization”, https://www.intel.com/content/www/us/en/processors/xeon/delta-l-methodology-for-electrical-characterization-guide.html, Intel Corporation, ref. # 330223-001, Feb. 2014.

[6] J. Hsu, T. Su, K. Xiao, X. Ye, S. Huang, Y. Li, “Delta-L Methodology for Efficient PCB Trace Loss Characterization”, Microsystems, Packaging, Assembly and Circuits Technology Conference (IMPACT), 2014 9th International (pp. 113-116). IEEE.

[7] J. Hsu, T. Su, K. Xiao, X. Ye, S. Huang, Y. Li, “Printed Circuit Board Insertion Loss Measurement Metrology Comparison”, Microsystems, Packaging, Assembly and Circuits Technology Conference (IMPACT), 2015 10th International IEEE.

