A Modeling Approach for Predicting the Effects of Dielectric Moisture Absorption on the Electrical Performance of Passive Structures

Brian Curran,[1,]* Ivan Ndip,[2] Ege Engin,[3] Jorg Bauer,[2] Harald Pötter,[2] Klaus-Dieter Lang,[1,2] and Herbert Reichl[1,2]

Abstract—In this paper a modeling approach for predicting the electrical behavior of nonresonant and resonant structures under the influence of the absorption of moisture into the dielectric is presented. The paper focuses on the encapsulation materials used for printed circuit boards (PCBs) as a case study. For the investigated cases, analytical modeling shows that the loss of electrical insulation resulting from moisture absorption has minimal effects on the losses in transmission lines (TMLs), which would only cause system failure when combined with other aging effects. However, potential cases are discussed where the loss of electrical insulation could be significantly increased. Full-wave modeling shows that moisture absorption can cause the detuning of passive components, specifically antennas and impedance-controlled TMLs, that can have significant effects on system performance. Antenna resonance frequencies shift by up to 3-5%.

Keywords—Moisture absorption, dielectric modeling, composite dielectric, Lichtenecker equation

Introduction

Organic dielectrics absorb water when they are kept in environments with high temperature and humidity. Absorption of fluids into a dielectric was examined in [1]. The effects of moisture absorption and temperature on the dissipation factor, resistance, breakdown voltage, and relative permittivity for polyamide and other organic dielectric materials is shown in [2-6]. A study by Zhao et al shows the effect of moisture on the stability of the dielectric permittivity [7]. Studies by Wang et al [8] and Vogels et al [9] investigate moisture induced breakdown and failure in dielectrics. Various researchers have also studied the effects of moisture on mechanical properties, for example [10-12]. One concern that has been identified regarding moisture absorption is that moisture will settle on an interface between two dielectrics as the difference in expansion coefficients will form delamination and adhesion loss at the interface. This phenomenon was investigated in [13]. Monitoring of the mechanical properties of a substrate under the influence of moisture absorption with a method to test the stress

of a module is presented in [14]. A technique to reduce the mechanical stresses was presented by Fan et al [15].

Composite dielectric modeling techniques may also offer new approaches for modeling moisture absorbed into a polymer. A summary of different composite dielectric modeling techniques was offered by the authors in [16]. Goncharenko et al [17] also gives an analysis of the state-of-the-art techniques for determining the effective permittivity when moisture is absorbed into a dielectric. Both publications identify the Lichtenecker equation as an adequate technique for determining the effective complex permittivity of a composite dielectric. The Lichtenecker equation, eq. (1), is a technique for averaging the complex permittivities of the moisture, ε_1, and the organic substrate, ε_2. The result is an effective permittivity, ε_{eff}.

$$\varepsilon_{\text{eff}}^k = \theta \varepsilon_1^k + (1 - \theta)\varepsilon_2^k \tag{1}$$

A further theoretical analysis and justification is offered by Zakri et al [18] and a derivation from Maxwell's equations is presented in [19]. Kärner and Schütz [20] uses the Lichtenecker equation and theoretical absorption prediction, based on the Fick model, to predict the relative permittivity over time.

With composite dielectric modeling techniques, one can arrive at effective dielectric properties of a composite material. Various methods are used to model transmission line capacitance and dielectric losses once these composite dielectric properties are known. One example is the Chen and Chou [21] model that will be discussed in the section titled Analytical Transmission Line Modeling Considering Moisture Absorption.

While the effect of humidity absorption on the permittivity of a material has been widely studied, as well as thermomechanical properties, a modeling approach for the electrical properties of a dielectric based on moisture absorption has not been fully developed, especially one that includes frequency dependent losses. Only Hamilton et al [22] shows measurements of frequency dependent losses dependent as a function of humidity. In his paper, he highlights the problem by showing a significant increase in the loss tangent. Although this is a very important observation, the paper still offers no method for predicting the electrical impact of moisture absorption. The effect of humidity on the electrical characteristics of passive high frequency (HF) structures has also not been investigated.

In this paper, a novel modeling approach for predicting the electrical performance of passive structures after dielectric moisture absorption is presented. In a previous paper [16], the

authors studied the effects of moisture absorption on the relative permittivity and loss tangent of polymers, a technique that will be further used in this paper. The main contributions of this paper are:

1. Proposing a systematic approach for predicting the impact of moisture absorption on resonating and nonresonating passive structures used for RF system design.
2. Presenting and illustrating a case study of the modeling of transmission lines in mixed dielectrics considering the impact of moisture absorption.
3. Studying the impact of moisture absorption on the resonating and radiating properties of two different antenna configurations, namely microstrip patch and dipole.

The remainder of this paper is structured as follows; in the next section, the modeling approach for predicting impact of moisture absorption on performance of passive structures is presented. After that, a very brief summary of the effects of moisture absorption on polymers is given, as published in [16]. The next sections cover in-depth investigations on the impact of moisture on transmission lines and antennas.

MODELING APPROACH FOR PREDICTING THE PERFORMANCE OF PASSIVE STRUCTURES CONSIDERING MOISTURE ABSORPTION

The modeling approach used for modeling the moisture dependent high-frequency response of a passive structure is shown in Fig. 1. The first step of the modeling approach is to define the structure to be modeled. The second step of the modeling approach is to identify potential composite dielectrics. When moisture is absorbed, it becomes a composite dielectric of water and polymer. When those materials are identified, the amount of moisture that they absorb must be measured or estimated. Saturation absorption can be determined by weighing a sample material, submerging it in water, and weighing it periodically until its weight no longer increases. Moisture absorption rates can be determined using other techniques, such as those described in [1-6]. The mass
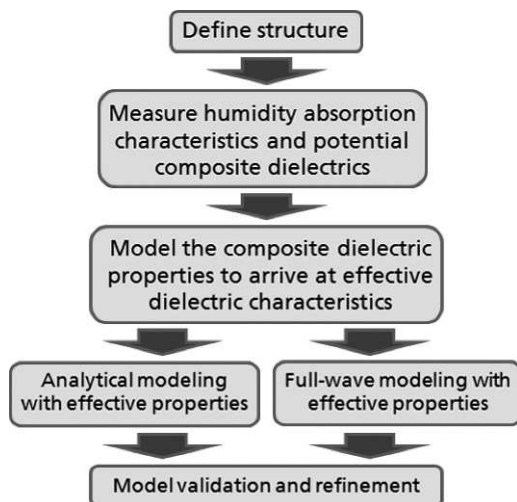

Fig. 1.   Modeling approach for the modeling of moisture dependent modeling of high-frequency properties of passive structures.

ratio must be converted to the volume ratio to be used in the Lichtenecker model.

Using the moisture absorption information, frequency dependent effective dielectric properties can be calculated using a composite modeling technique (this paper uses the Lichtenecker Equation).

When the frequency dependent complex dielectric constant is known, it can be applied in traditional models for passive high-frequency structures, for example, analytical transmission models or full-wave simulations. The modeling should then be validated with measurements and can be refined based on the results of the measurements.

Possible outcomes of this modeling approach are (1) measures that can reduce the impact of humidity absorption in a package, or (2) confirmation that humidity absorption will not lead to significant performance degradation.

MODELING OF COMPOSITE DIELECTRIC PROPERTIES

The results given in eq. (2) and eq. (3) were used to calculate complex permittivity of the moisture. Conductivity of water leads to a frequency dependent $\tan\delta$ as in eq. (4). This frequency dependent $\tan\delta$ is used to make a frequency dependent, complex permittivity, as in eq. (2). Water behaves as a semiconductor and these same equations have been used to model complex permittivity of silicon, for example in [23]. The polymer is modeled with only eq. (2), which leads to a frequency independent permittivity. These permittivites can then be applied in eq. (1) to arrive at a composite complex frequency dependent permittivity.

$$\varepsilon = \varepsilon_0 \varepsilon_r (1 - j \tan \delta) \qquad (2)$$

$$\tan \delta = \tan \delta_d + \frac{\sigma}{\omega \varepsilon_0 \varepsilon_r} \qquad (3)$$

To validate the Lichtenecker equation, an interdigital capacitor was modeled, fabricated, encapsulated with a polymer material that absorbs a known relative volume of moisture, and measured. When the value of k is 0.05 (very close to homogeneous absorption) then an interdigital capacitor modeled with Ansys HFSS, using the finite element method (FEM), matches very closely to measured values of capacitance and the parallel conductance. Modeled and measured capacitance and conductance is shown in Fig. 2a and 2b. More information is available in [16].

ANALYTICAL TRANSMISSION LINE MODELING CONSIDERING MOISTURE ABSORPTION

Modern multilayer packages often have several dielectric layers, above and below the metallization layer, with different permittivities and loss characteristics. Chen and Chou offer a model based on conformal mapping techniques for modeling the capacitance of a coplanar waveguide. Then, using the theory of superposition of capacitances, Chen expands the model to include multiple dielectric layers above and below the metallization layer, similar to the structure in Fig. 3. The Chen model was used to model the capacitance of the dielectric of an example coplanar transmission line with typical thin-film dimensions on a glass substrate with a polymer encapsulation
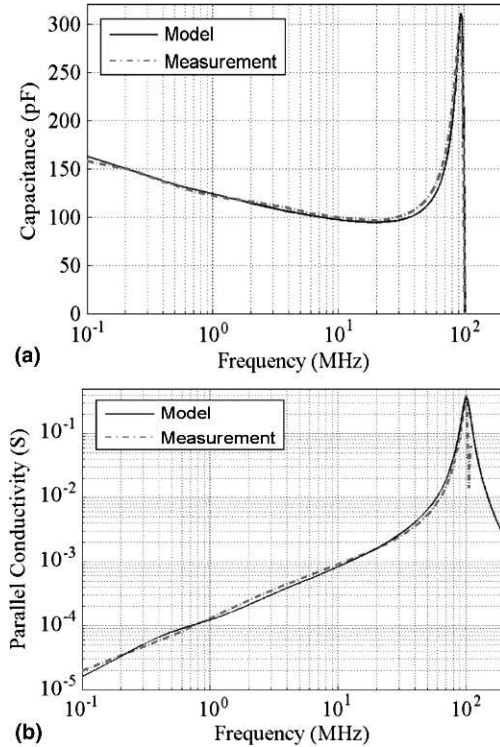
Fig. 2. Humidity dependent dielectric characteristics of an interdigital capacitor measured and modeled with a full-wave simulation, (a) capacitance, (b) conductance.

material [21]. This type of structure has applications in 3D miniaturized sensor nodes.

The structure that will be investigated is shown in Fig. 3. It is a benzocyclobuten (BCB, $\varepsilon_r = 2.6$, tan$\delta = 0.006$) redistribution layer, constructed on a glass substrate ($\varepsilon_r = 4$, tan$\delta = 0.001$), with a thin SiO$_2$ ($\varepsilon_r = 4.4$, approximated as lossless) layer between. Above the redistribution layer is a thin film coplanar transmission line with a polymer encapsulation material on top. The encapsulation material has saturation absorption of 5% water by mass (which is a realistic value for an epoxy). The dielectric structure has both losses from dielectric loss mechanisms (tanδ) and dielectric conductivity (σ of moisture).

In the case of the glass, SiO$_2$, and BCB layers, eq. (2) was used to determine a complex but frequency independent ε_r. For the encapsulation material, eq. (3) was used to find a frequency dependent tanδ for the moisture, then eq. (2) was used to find the complex frequency dependent ε_r of the moisture and the complex frequency independent ε_r of the polymer. Then the
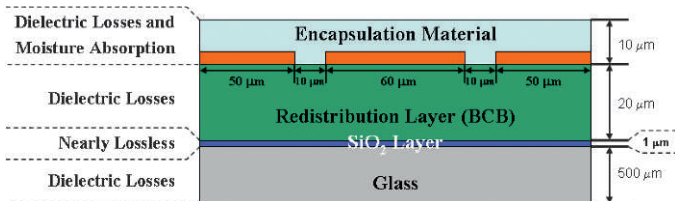
Lichtenecker equation, eq. (1), combines the moisture and polymer permittivity, resulting in a complex frequency dependent composite permittivity for the encapsulation material.

The resistance of the transmission lines was neglected in order to only investigate the dielectric losses. The conductor, therefore, was represented only with an analytically calculated inductance. Rather than representing the dielectric as a capacitance and a conductance, it is represented as a complex capacitance, where the real part represents the capacitance and the imaginary part signifies the losses.

$$\gamma = \sqrt{\left(R' + j\omega L'\right)\left(G' + j\omega C'\right)} \tag{4}$$

$$\gamma = \sqrt{\left(R' + j\omega L'\right)\left(j\omega\left(C_R + jC_I\right)\right)} \tag{5}$$

$$\alpha_d = \mathrm{Re}\sqrt{\left(j\omega L'\right)\left(j\omega\left(C_R + jC_I\right)\right)} \tag{6}$$

Starting with the traditional equation for the propagation constant, γ, for a TEM wave, eq. (4), we replace the conductance and capacitance of the dielectric with only the complex capacitance, eq. (5). To initially neglect the lossless conductor, the conductor is approximated as only a per-unit-length inductor and we arrive at the dielectric attenuation of the coplanar transmission line, eq. (6).

First, the k variable in the Lichtenecker equation, which represents the isotropy of the moisture absorption, was investigated using the Chen model discussed previously, to see the influence of the homogeneity of the moisture. Three values were used. To simulate an encapsulation with homogeneous moisture diffusion, $k = 0$ was used. To investigate moisture completely inundating an interface, $k = 1$. To simulate moisture that is partially homogeneous, a value of $k = 0.5$ was chosen. The results are shown in Fig. 4.

In Fig. 4, it is shown that the losses begin in the MHz range and increase but then level off. Galvanic losses, as a result of conductivity in a dielectric, are usually frequency independent. However, in our case, the dielectric is a composite and the polymer dielectric material isolates the TML from galvanic losses at lower frequencies. This is also the reason why the homogeneity of the moisture absorption has such a strong impact on the loss characteristics. It becomes apparent looking at Fig. 4 that absorption that is inhomogeneous ($k > 0$, which could result from moisture settling on an interface after delamination or adhesion loss), results in much higher losses than moisture that is homogeneously absorbed. In this case, the composite dielectric is behaving as an MIS structure with a

Fig. 3. Coplanar transmission line structure used to demonstrate the modeling approach.
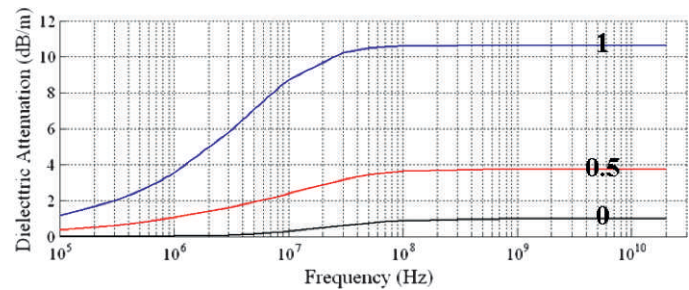

Fig. 4. Dielectric attenuation from moisture for three different mixing constants ($\sigma = 0.25$ S/m).
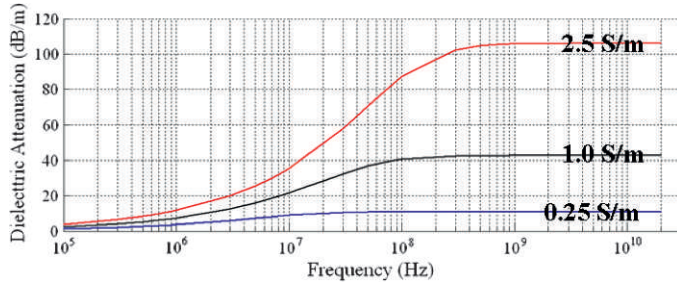
Fig. 5.   Dielectric attenuation from moisture for three different moisture conductivities ($k = 1$).

Fig. 7.   Sources of the dielectric losses in the structure in Fig. 6. (1) Moisture (parallel isotropic), (2) moisture and silicon, (3) moisture, silicon, and encapsulation, (4) moisture, silicon, encapsulation, and BCB.

slow-wave characteristic, and this becomes more exaggerated at low frequencies.

The second investigation looks at the conductivity of the moisture. Conductivity of water is related to the amount of ions present. If there are ions in the encapsulation material during fabrication, or if there are ions in the air or moisture during the absorption, then the conductivity of the moisture will vary. The results for three different conductivities are shown in Fig. 5.

The trend remains the same as the conductivity increases. At low frequencies, the dielectric losses from the moisture remain negligible. In the MHz frequency range, they increase and level off. The higher the moisture conductivity value, the higher the losses. It is also a linear relationship. When the conductivity doubles, the stabilized value of the losses from the moisture also doubles. And for high conductivities, especially above 1 S/m, the losses become significant in comparison with conductor or dielectric losses from dielectric loss mechanisms.

The next investigations aim to show the dielectric losses in comparison with each other. The first structure that was investigated with this model was a coplanar line, packaged using thin-film technology, and encapsulated with a polymer underfill. The specific dimensions are shown in Fig. 6.

For the calculation of the dielectric losses, the underfill material is assigned 5% moisture absorption and in the Lichtenecker equation, $k = 1$. This is designed to simulate moisture settled onto the dielectric interface between the encapsulation material and redistribution layer. Moisture conductivity is 0.25 S/m, which is what was observed in the measurements published in [16].

In the buildup in Fig. 6, we see that the galvanic losses for silicon and the losses for the moisture have similar trends, shown in Fig. 7, trace (1) and (2), except that polarization
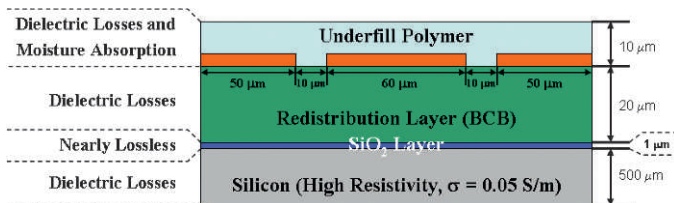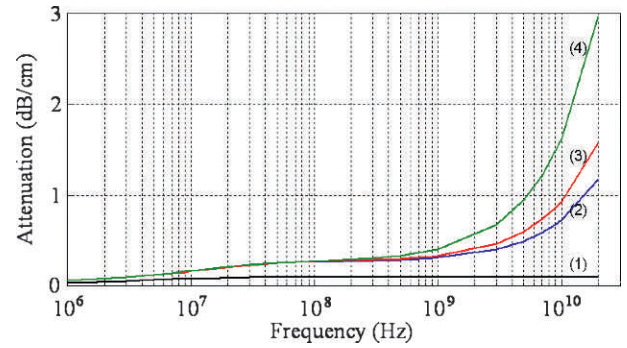
losses in the silicon are introduced in the GHz frequency range. This can be expected because they are both semiconductive dielectrics that are separated from the conductor by an isolation layer.

FULL-WAVE MODELING OF PASSIVE STRUCTURES

To predict the effects of moisture absorption on the electrical performance of resonant structures, full-wave simulations were conducted. The full-wave simulations were executed with Ansys HFSS, a full-wave solver using FEM.

It was shown in the previous section that the effects of moisture absorption tend to be frequency dependent at lower frequencies (in our case, up to around 200 MHz) but the frequency dependence stabilizes at higher frequencies. Therefore, the authors expect the following modeling techniques to remain valid at higher frequencies in the multiple GHz range. Two antenna models were designed in HFSS to radiate at 2.5 GHz. The first antenna model was a traditional patch antenna excited by a microstrip line. Both antennas were built on an FR4 substrate. The antenna is then encapsulated with an epoxy resin, $\varepsilon_r = 4.4$, which absorbs moisture. A picture of the antenna model is shown in Fig. 8 (top). The second antenna model was a simple dipole antenna, excited with a lumped port, without a ground plane, also encapsulated with an epoxy resin, ($\varepsilon_r = 4.4$). This antenna model is shown in Fig. 8 (bottom).

The frequency dependent dielectric material properties of the encapsulation material were determined analytically using the technique described in the second section of this paper, a complex permittivity was calculated with eq. (2), in case of the FR4. In the case of the encapsulation material, as with our transmission line examples in the previous section, complex permittivities for moisture and polymer were calculated using eq. (2) and eq. (3), which were combined using eq. (1) into a frequency dependent complex permittivity. These frequency dependent permittivities were defined as the dielectric material properties during the simulation. The simulations were conducted three times for each antenna. The first time, they were conducted assuming no moisture absorption, the second time assuming 2% moisture absorption by mass, and the third time, the simulations assumed 4% moisture absorption by mass. The variable $k = 0.05$ (nearly homogenous absorption)
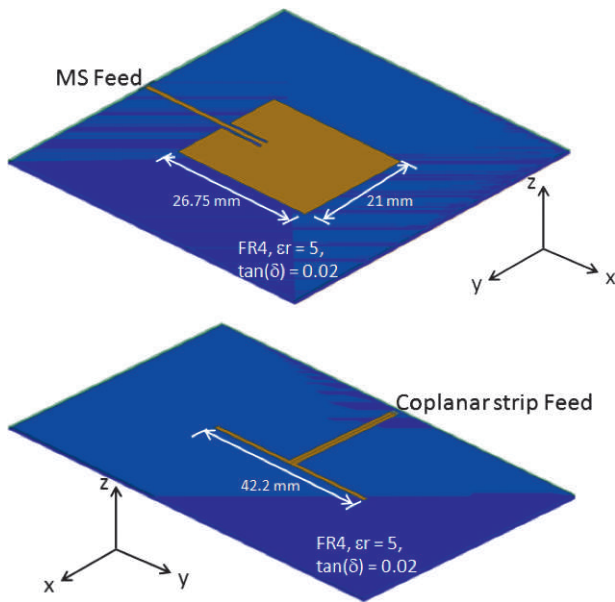

Fig. 6.   Realistic dielectric buildup for 3D integration on a high resistivity silicon interposer.

Fig. 8. Patch antenna (top) and dipole antenna (bottom) models used in full-wave simulations.

and $\sigma_{moisture} = 0.25$ S/m because those were the values determined by the experimental validation described in the second and in more detail in [16]. These values are then known to be realistic. These values result in an increase of encapsulation
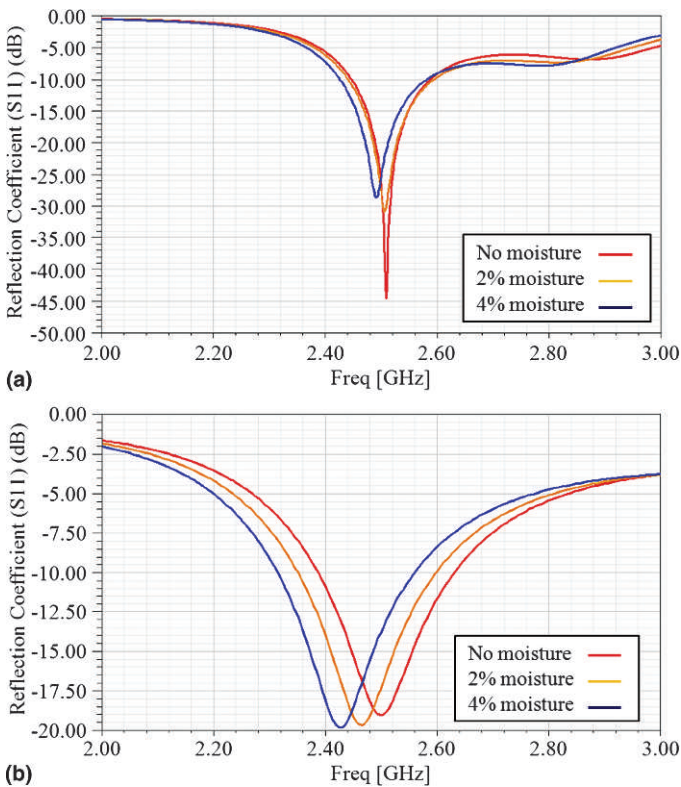

Fig. 9. Response of the antenna reflection coefficient, (a) patch antenna, (b) dipole antenna.
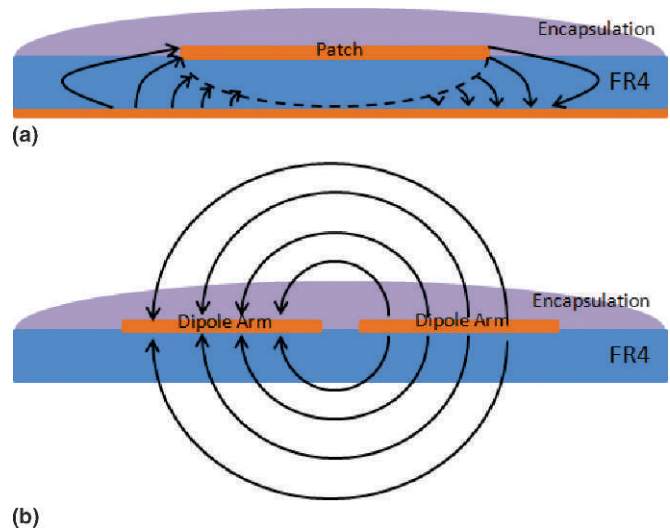

Fig. 10. Electric field diagram (a) patch antenna cross section, (b) dipole antenna cross section.

polymer ε_r from 4.4-4.95 and 5.55 respectively at 2.5 GHz. The results of the simulations are shown in Fig. 9.

In Fig. 9a, we see that the resonant frequency of the patch antenna shifts to lower frequencies when moisture is absorbed into the encapsulation materials. This is expected because the moisture absorption increases the dielectric permittivity of the encapsulation material, forcing a slight decrease in the resonant frequency. The effect, however, is very small. After the absorption of 2% moisture, the resonant frequency shifts less than 0.2% of the original frequency. After 4% moisture absorption, the shift increases to approximately 0.7%.

Fig. 9b shows the simulations of the dipole antenna input reflection. In this case, the same effect can be seen where the resonance shifts to lower frequencies as moisture is absorbed into the epoxy. The effect on a dipole antenna is more significant, with 2% moisture absorption resulting in almost a 2% decrease in resonance frequency and 4% moisture absorption resulting in a about a 3% decrease in the resonant frequency.

It can be expected that moisture absorption in an encapsulation material would have a much larger effect on a dipole antenna than a patch antenna. A patch antenna resonates under the patch, between the metal patch and a metal ground plane underneath, as we see in Fig. 10a. The encapsulation material
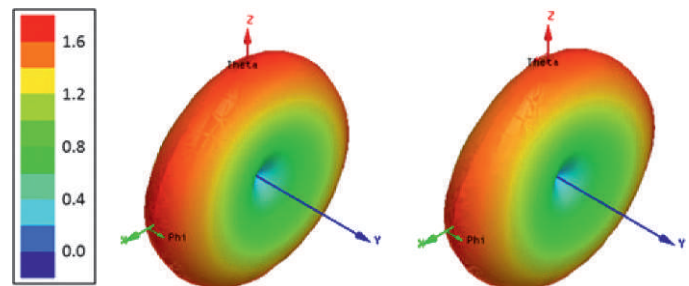

Fig. 11. Gain of a dipole antenna, before moisture absorption (left), after moisture absorption, with a 4% uptake (right).

only affects the resonant frequency due to small edge effects. Nearly the entire electric field exists under the patch, which we have modeled as having no moisture absorption. A dipole, however, functions differently. A dipole has no ground plane, so the properties of the FR4 and the encapsulation material have an equal effect on the resonant frequency. As we see in Fig. 10b, the field is equally distributed in the FR4 and in the encapsulation polymer. As a result, the moisture absorption in the encapsulation material can have a significant effect on the electrical performance.

Fig. 11 shows the antenna gain of the same dipole antenna. Although we see a change in the resonant frequency, there is no discernible difference in the gain characteristics of the antenna. One would expect other antenna characteristics, like the directivity, to remain the same (note that Fig. 11 shows that absolute gain remains unaffected; realized gain, not shown, which includes reflective losses, would be affected by a detuning of the antenna). The antenna is being detuned to a different resonant frequency, which would not affect the function or directionality of the antenna.

CONCLUSION

This paper uses a combination of analytical composite dielectric modeling techniques, analytical transmission line modeling techniques, and full-wave simulations to analyze the effect of moisture absorption on the electrical characteristics of a passive structure in a package, with special attention to moisture absorption in encapsulation materials. Coplanar TMLs and planar antennas were offered as examples.

The modeling approach has shown that moisture absorption will typically have little effect on the electrical insulation in a transmission line. However, the paper identifies two potential scenarios where a significant loss of electrical insulation can occur:

1. When moisture absorption is not isotropic, for example, delamination or cracking in the encapsulation material.
2. When ions in the air or encapsulation material lead to a higher moisture conductivity.

Another scenario that can lead to performance degradation in transmission line structures would be the detuning of impedance controlled transmission lines on PCBs in the 100 MHz to the multiple GHz range.

Full-wave simulations have investigated the effects of moisture absorption on resonant structures, with narrow bandwidth resonant antennas as an example. These simulations show that performance of resonant structures can deteriorate from moisture absorption in their encapsulation material. This effect is strongly dependent on the type of structure being investigated. Packages and components can often be chosen or designed explicitly to remain robust against moisture absorption.

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