

Electrical Losses in Coaxial Cable

R. F. Eaton and C. J. Kmiec

The Dow Chemical Company, Wire and Cable R&D

171 River Road, Piscataway, NJ 08854

+1-732-563-5056 / eatonrf@dow.com +1-732-563-5129 / kmieccj@dow.com

Abstract

As coaxial cables are used at ever higher frequencies in the Gigahertz range, cable losses become extremely important. Losses are functions of both Dk, dielectric constant, Df, tangent delta, of the polymer and the geometry of the cable construction. Control of the polymer architecture and additive package can reduce electrical losses in the cables fabricated from the polymer resulting in lower cable losses.

Dk of a polymer is related a variety of chemical properties of the polymer: polarity, Tg, Tm etc. Df of a polymer is related to molecular motions of polar groups either along the polymer chain or the motion of polar molecules within the polymer matrix. We will discuss the Df contributions of the alpha, beta and gamma transition in polyethylene. Dk and Df are also functions of frequency and temperature.

Keywords: Coax; Dielectric Constant; Dissipation Factor; Polyethylene; Power Loss; Tan Delta.

1. Introduction and Coaxial Cable

Background

Coaxial cables are an important growing segment for the W&C industry. This report is a review and summary of the key parameters that control signal loss in COAX cable. We will show that chemistry fundamentals can be used to reduce losses in the resins to fabricate the coaxial cables.

Intuitively one would expect electrical losses to be related to the dielectric tangent delta at the frequency of interest. If the polyethylene contained no polar groups, the various polymer molecular motions, the alpha, beta and gamma transitions in polyethylene and related polyolefins, would have little or no dielectric loss. Literature data shows the electrical tangent delta of a polyethylene is related to level of polar impurities in the case of polyethylene¹.

2. Coax Cables by Gas Injection Process

For over many years Coaxial cables have been used in the transmission of Community Antenna Television (CATV) and radio frequency cables. Both solid and foamed dielectrics are used for coax insulation. Foamed cable has lower electrical losses but is more susceptible to environmental degradation especially moisture pickup. The current foam process that is utilized requires a specialized process wherein typically nitrogen gas is injected via sonic technology into the polymer melt. Incorporation of the gas leads to creation of a foam with expansion levels reaching 70-80%. Coaxial cable is used to transmit a signal (voice, video or data) received from head end/antenna to a final destination. Coaxial cables are used in a number of high frequency applications including:

Traditional 75 ohm impedance cables include:

CATV applications including aluminum jacketed CATV 'hard line'

Drop: US MIL spec RG59, RG6, RG7, RG11

Distribution

Trunk

Video cables including component video and SPDIF cables

50 ohm RF cable for mobile telephony

LAN/Computer cable

Two way communication cable

A typical COAX cable design is shown in Figure 1.

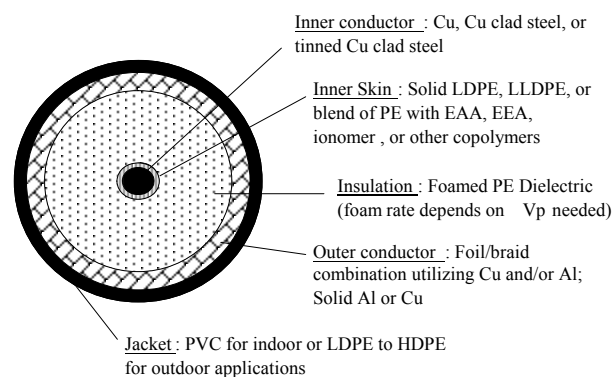


Figure 1: COAX Cable

The key principle of sonic gas injection for COAX cables is to have consistent flow of nitrogen gas through the gas control system in order to obtain the uniform critical cable performance. The gas control system allows gas which flows through a constricting nozzle to reach critical pressure (Pc) wherein the gas flow rate becomes independent of melt pressure.



Calculation for the critical pressure for nitrogen is $P_c = 0.53 * P_a$

The volumetric gas flow rate required to achieve a given expansion level can be determined for any given set of production requirements. Using the values for Extrusion line speed (LS), Insulation cross-sectional thickness (XSA) and Base and foam resin density (BD, FD) and then incorporating these values into the basic equation for SONIC gas injection:

$$D^2 P = c_1 * LS * XSA * \left(1 - \frac{FD}{BD}\right)$$

Where c₁ = constant

One can then determine the gas pressure (P) and orifice size (D) needed to achieve desired foaming

3. Materials Used in Coax Insulation

Coaxial Cable Insulation Materials

Coaxial cable insulation is generally a mixture of High Density Polyethylene (HDPE), High Pressure Low Density Polyethylene (LDPE) and a nucleating masterbatch. In general the ratio of HDPE to LDPE is 70-80% HDPE/30-20% LDPE. The nucleating masterbatch is typically added at about 1-3% and is generally also based on a LDPE resin.

The HDPE Polyethylene products known as High density polyethylene (HDPE) are manufactured primarily by a low pressure catalyst polymerization process. The low pressure technology was first developed in the late 1970's and is widely utilized by man polyethylene manufacturers. The following Figure 2 illustrates a schematic of a typical low pressure manufacturing process.

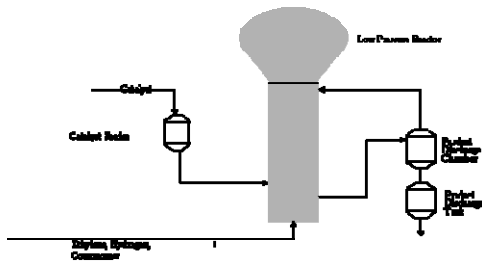


Figure 2: Low Pressure Polyethylene Process

HDPE is produced in a polymerization process at pressures typically about 300 psi and temperature of about 100°C.

The LDPE Polyethylene products known as low density polyethylene (LDPE) are manufactured exclusively by high pressure free radical polymerization. The high pressure technology was first introduced in the late 1930's and is the oldest of the polyethylene manufacturing technologies.

LDPE is produced in a bulk polymerization process at pressures typically at 35,000 psi and a temperature of around 300°C. The following Figure 3 illustrates a schematic of a typical low pressure manufacturing process.

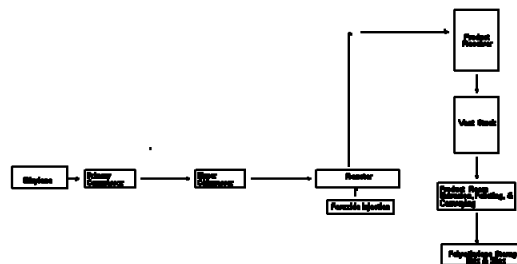


Figure 3: High Pressure Polyethylene Process

4. Definition of Electrical Power Loss

In this study we will use simple equations to evaluate the influence of DC and DF on the decibels/100 ft of electrical loss of a commercial coaxial cable. The decibel or db is simply the 10 times log of the ratio of power input to the cable at one end to the power available at the other end of the coax:

Db = 10 log10 [(Power output)/Power input)]

For example:

-3 db = 1/2 of the input power is available at the output of the cable

-10 db = 1/10 of the power is available at the output of the cable

-30 db = 1/1000 of the power is available at the output of the cable

5. Loss Data

Data was obtained from published sources². We fit various functions to evaluate the functional dependence of the dielectric loss on input frequency. Data Points were taken from Reference 2 and fit in Excel. The fit to a power law equation was excellent as shown in Figure 4.

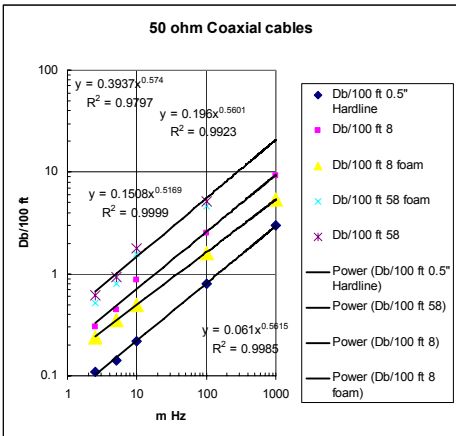


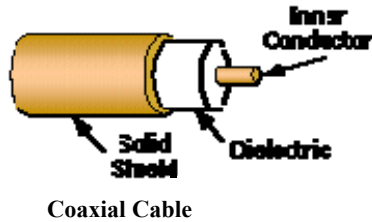
Figure 4, Power Law Fit to Cable Loss Data:

Table 1 Summary of Power Law Fit of Coaxial Cable Data from Figure 4.

Cable Type	Pre Exponential Factor	Exponent
RG-58	0.394	0.574
RG-58 Foam	0.331	0.587
RG 8	0.196	0.56
RG-8 Foam	0.151	0.517
Hardline	0.061	0.562

As illustrated in Figure 4 and Table 1, losses appear to vary with the 0.5 power of frequency. The basis of this dependence will be described next.

In general the equations below describe the calculated coaxial cable loss as a function of both frequency and cable geometry. The losses in decibel, db, per 100 feet depend on several geometric factors and both the dielectric constant and tan delta for the polymer³.



$$Db/100 \text{ ft} = k_1 \sqrt{F} + (k_2 * F) \quad (1)$$

$$k_1 = \left[0.4343 / (Z_0 * D) \right] * \left[(D / d * k_s) + F_{bd} \right] \quad (2)$$

$$k_2 = (2.78 * df) / V_p \quad (3)$$

F = frequency mega Hz

Z_0 = nominal impedance = $(60 / (\text{Sqrt}(DC))) * (\ln[D/(d * k_s)])$ for air dielectric $Z_0 = 60 * \ln(b/a)$

a = od of inner conductor; b = id of outer conductor

D = dielectric diameter (id of outer conductor, shield)

d = center conductor diameter

$k_s = 1.0$ for solid center conductor

F_{bd} = braid factor (= 1.0 for solid 'tube' braid)

DF = dielectric loss (electrical tan delta)

V_p = velocity of propagation = $1 / \text{Sqrt}(DC)$

DC = Dielectric Constant

Db = decibel = $10 * \{\log_{10} [\text{Power}(\text{out}) / \text{Power}(\text{in})]\}$

Larger diameter cables like RG-8 and 'Hardline' have lower losses than smaller diameter cables like RG-58. Foamed polyethylene dielectric has a lower loss, RG-8 foam, than solid polyethylene dielectric RG-8.

A -3 db loss means 50% of the input power is dissipated in the coaxial cable. Losses > 3 db/100 ft are quite significant. Low loss conserves transmitter or amplifier power. For a given geometry, one term for db/100 ft electrical losses varies with the square root of frequency. This k_1 term in equation 1 above is due to the 'skin effect', the property of electromagnetic waves to travel near the surface of the conductor, usually copper or silver. The skin effect varies with the square root of the applied frequency. The depth of penetration of the electromagnetic wave is frequency dependent as shown in the Figure 5 plot below:

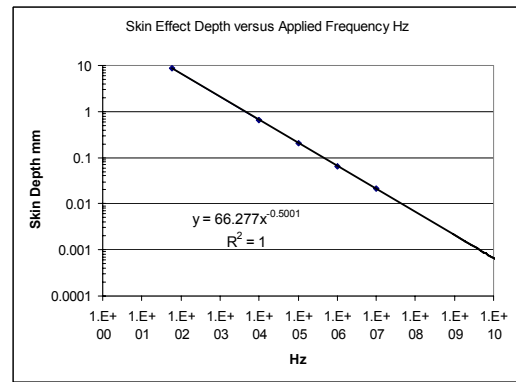


Figure 5: Skin Effect Depth versus Frequency

We now see that the electrical loss dependence on the square root of frequency is due to the skin effect. The k_1 term in Equation 1 depends on the dielectric constant of the dielectric polymer through the impedance term Z_0 , the nominal impedance. By inspection we see that: larger DC implies larger k_1 which larger slope of the plot of log (db/100 ft) versus log frequency. The larger slope results in higher dielectric loss at higher frequencies. Coax diameter impacts the pre-exponential factor of the log-log plot of db/100 ft versus frequency. This again is due to the skin effect: larger diameter inner conductor and larger outer shield 'pipe' have a larger surface = lower 'surface resistance' to dissipate electromagnetic energy.

The raw data in Figure 4 and the derived equations from Figure 5 can now be understood, much of the loss in coax is due to the skin effect.

Although Equation 1 does not specifically account for 'ohmic' type direct current losses, that loss can be calculated directly from specifications for ohmic resistance of the cable: 0.148 ohms/100 ft. If we assume the source produces 1000 watts of power, only 2.98 watts is lost due to $I^2 * r$ (ohmic) losses. This is a loss of only 0.0129 db/100 ft. The loss is actually about 2 db/100 ft. Ohmic losses are only a small component of the total db/100 ft loss.

Intuitively we expect losses in coax to also vary with the electrical tan delta since tan delta represents electrical dissipative mechanisms within the polymer often caused by molecular motions of polar groups either attached to or dissolved in the polymer chain. Usually both electrical and mechanical tangent delta peaks can be observed for a given molecular motion; if the polymer does not contain polar groups the electrical loss of the motion may not be observed. The influence of polar groups on electrical losses in polyethylene's has been published by Sato in Reference 1. That work focused on the dependence of tan delta on the presence of polar groups within the polyethylene. Next we will model the quantitative dependence of cable loss on tan delta. For mathematical simplicity we will only model a 'solid tube' coax, not the braided outer conductor type.

5.1 Simulations of the Impact of Polymer DF Parameter on Cable Losses versus Frequency

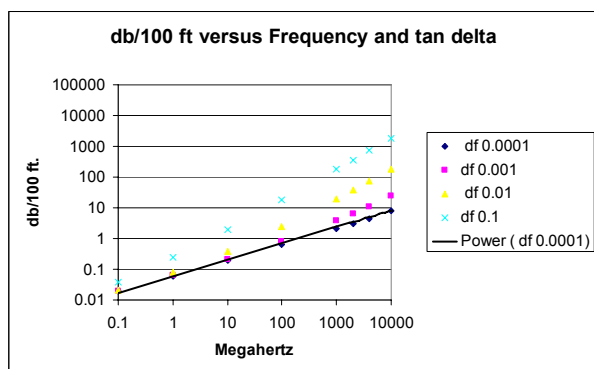


Figure 6: Influence of polymer tan delta on Cable Losses

Clearly tan delta (Figure 6) plays a larger role in electrical loss as frequencies approach the gigahertz region (1000 megahertz). In Figure 7 we expand the resolution in the Gigahertz region. We see that tan delta values as low as 0.0001 have a significant impact on losses:

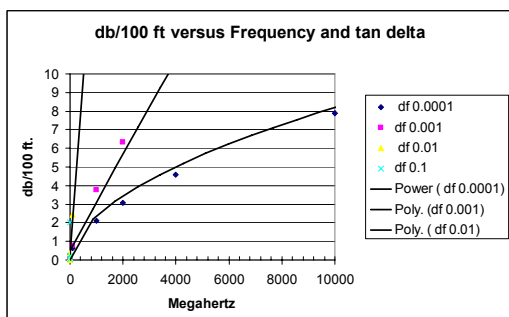


Figure 7: Cable Losses in the Gigahertz region, Influence of tan delta

If there were no polar groups like peroxide residue, antioxidants and thermal oxidation products present in the polyethylene tan delta would likely be in the ~ 0.00001 range.

The above work fundamentally assumes DF is frequency independent. This is not the case. At a given temperature the alpha, beta and gamma transitions in polyethylene are functions of measurement frequency. The gamma or 'crankshaft' transition^{4,5} occurs at $\sim -120^\circ\text{C}$ at 1 Hz. The using an Arrhenius relationship with an activation energy of ~ 13 kcal/mole, the gamma transition will be near the GHz range at 25°C . Polar groups in the vicinity of the gamma transition can move and cause electrical losses.⁶ The challenge is to minimize polar impurities in the polyolefin insulation material.

6. Polyethylene Characterization

The two critical properties of the polyethylene resins for coaxial insulation are low dielectric constant and low dissipation factor. DC is a function of crystallinity or density and increases as density increases. Dissipation Factor (DF) represents a signal loss

due to dissipation through the insulation. Dipolar impurities, end groups, chain folds and branch points increase the DF, as does increasing the measurement frequency. With the increased need for data and signal transmission in today's environment the frequency testing can reach upwards of 5-7GHz. The following Figures 8 & 9 represents the DC and DF values of HDPE materials which are utilized in the application today.

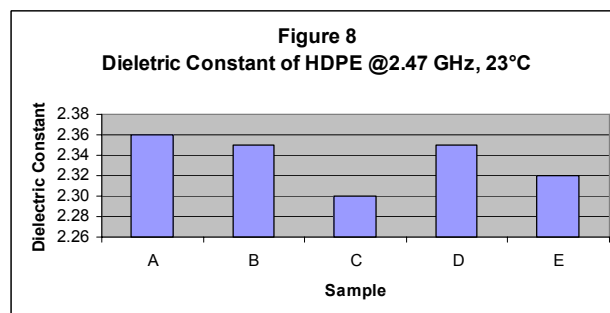


Figure 8: Dielectric Constant of HDPE @2.47 GHz, 23°C

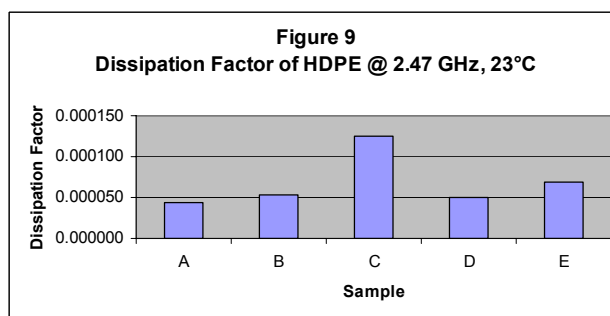


Figure 9: Dissipation Factor of HDPE @2.47 GHz, 23°C

Figures 10 and 11 represent the DC and DF values of HDPE materials which are utilized in the application today

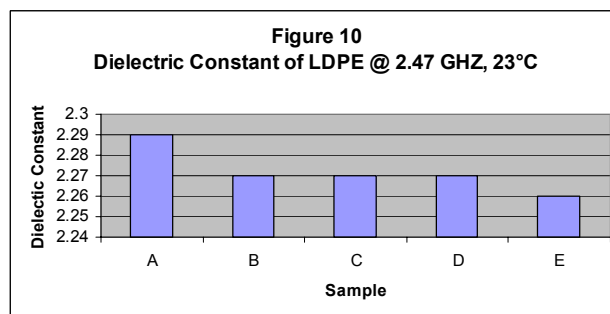


Figure 10: Dielectric Constant of LDPE @ 2.47 GHz, 23°C

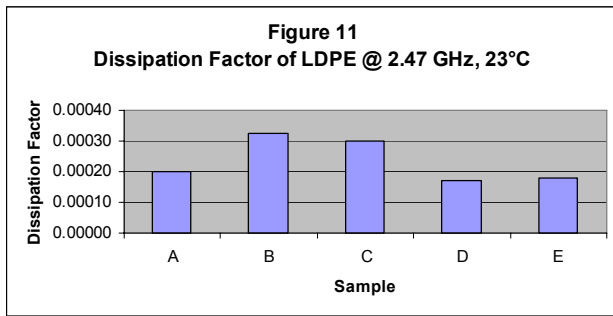


Figure 11: Dissipation Factor of LDPE @ 2.47 GHz, 23°C

COAX insulation as noted previously is a mixture of HDPE and LDPE. Thus looking at the varying data in Figures 8-11, one can ascertain that the selection of the proper polymers can have an significant effect on the overall cable signal loss.

7. Optimization of LDPE Resins

Initial studies were centered on the improvement in the LDPE component of the system was an area of focus. Effort in this area showed that LDPE electrical performance can be influenced by the type and efficiency of a specific LDPE reactor. Samples of similar LDPE were secured from different types of reactors and DC and DF at 2.47 GHz measurements were again obtained. The resulting data is illustrated in Figures 12 and 13.

Reactor operation is affected by the typical reaction parameters one normally sees in reaction chemistry. These include but are not limited to time, temperature and pressure. Thus as shown in Figure 13, one can see that not all reactors produce the same type of electrical performance when making similar LDPE products. In addition the LDPE being primarily a non polar aliphatic hydrocarbon, which during polymerization can also incorporate polar functional groups from various sources. Examples of these sources include can include organic peroxides types and chain transfer agents which are known to also influence electrical performance.

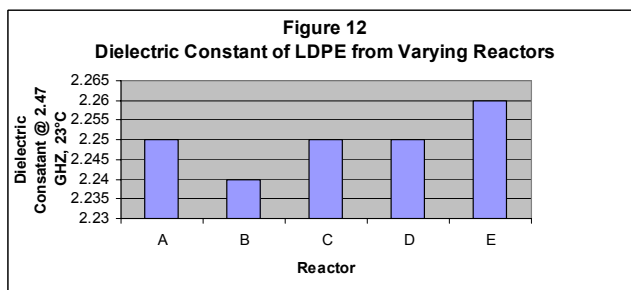


Figure 12: Dielectric Constant of LDPE from Varying Reactors

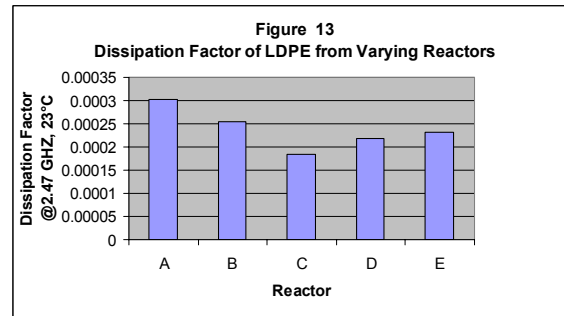


Figure 13: Dissipation Factor of LDPE from Varying Reactors

In focusing on reactor optimization a study was performed wherein we adjusted conditions on a single reactor to further illustrate that electrical performance can be influenced or improved by the reaction kinetics. We established an internal analytical test method to track the performance of the reactor which we define as the Product Performance Factor wherein the lower the number the better the performance. Thus in product optimization studies we followed the reaction by securing samples and tracking the Product Performance Factor. 2.47 GHz DC and DF data was generated on these samples and is illustrated in Figure 14.

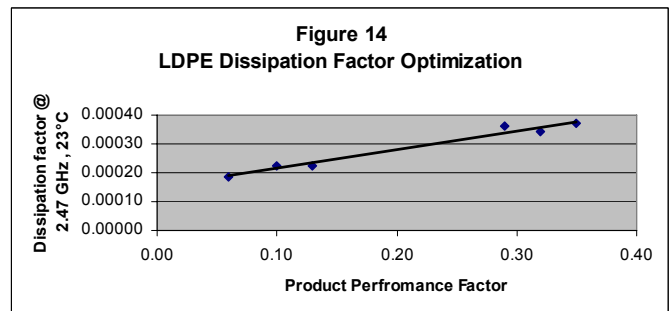


Figure 14: LDPE Dissipation Factor Optimization

As observed the dissipation factor can be significantly influenced by the high pressure reaction, thus indicating that optimization control of the reaction is required to obtain the lowest electrical loss of the LDPE.

8. Conclusions

- We have shown that for a given coax diameter and skin effect losses, an increase in polymer tan delta will negatively impact coax loss especially in the gigahertz region where tan delta losses can overpower skin effect losses.
- Optimization of a polyethylene reactor train can significantly decrease the electrical loss of the polyethylene in the GHz frequency range.
- We have developed a direct relation between 2.47 GHz tan delta and a chemical product performance factor which can be used to optimize, minimize, dielectric losses in the product LDPE.

9. Acknowledgments

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10. References

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11. Pictures of Authors



Robert F. Eaton, 171 River Rd.,
Piscataway, NJ 08854

Bob Eaton is a Research Leader in Dow's Wire and Cable Research Group. He has a Ph.D. in Polymer Chemistry from Princeton University and did post doctoral research in Polymer Physics at UC Berkeley. His research interests include polymer structure property relations,

electrical properties of polymers and 'green' chemistry. He is an active Amateur Radio enthusiast.



Chester J. Kmiec, 171 River Rd.,
Piscataway, NJ 08854

Chester Kmiec. is a Development Leader for the Wire and Cable Compounds group of The Dow Chemical Company. Chet has 34 years experience in Polymer Applications Research and Development, the last 19 years at The Dow Chemical Company. He holds a B.S in Plastics

Technology from Lowell Technological Institute and an M.B.A. from the State University of New York at Buffalo. . In his current position as the Telecommunication Cable Materials Application Technology Leader, Chet is responsible for leading the development and commercialization of new product technology for Telecommunication cable applications. He is holds 17 patents.