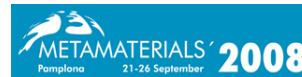


Complex Effective Permittivity of Carbon Loaded Dielectric Films with Printed Metallic Square Rings

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Metamaterials'2008 – Second International Congress on
Advanced Electromagnetic Materials in Microwaves and Optics
Pamplona, Spain, September 22-26, 2008

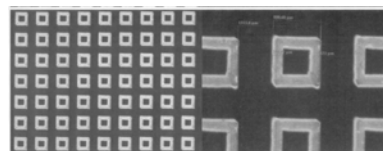


Sponsored by the Army Research Laboratory (DAAD19-02-2-0011) and the National Science Foundation through an EPSCoR Research Infrastructure Improvement (EPS-0554609) grant.



Engineered Resistive Surfaces

- The quest of this work is to produce lossy films with **adjustable surface impedance**: Perhaps isotropic and uniform; perhaps spatially varying; perhaps anisotropic; etc.
- Methods to realize such films include:
 - Printing electrically small, metallic patterns on commercially available films to reduce the effective surface resistivity. [Films include DuPont's Kapton XC[®] or Ohmega Technologies OHMEGA-PLY[®] or 200 Ω/sq stainless steel coated PET (polyethylene terephthalate), for example.]
 - Directly manufacture. Expensive, difficult to realize spatially varying.
- Focus of this work is on designing and producing **adjustable surface impedance** on commercially available resistive films. Will be using additive “direct-write” printing.



Open loops print quicker and use less conductive “ink.”

Printed by T. Amert, SDSMT





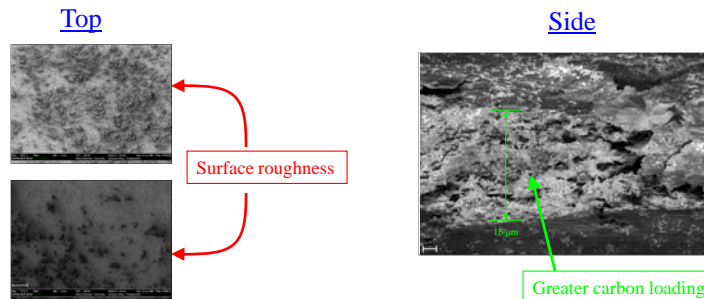
Outline

- Properties of Kapton XC®:
 - Physical morphology
 - Measured dielectric constant and conductivity of Kapton XC®
 - Irreversible temperature effects of Kapton XC®
- Flanged X-band waveguide measurement system
- Carbon loaded dielectrics: Increase **both** effective ϵ' and ϵ'' of highly percolated lossy films by printing metallic patterns
- Maxwell Garnett modeling for the effective ϵ' and ϵ''
- Measurements for engineered R card
- Commixture: Hybrid-mixture films
- Conclusions



Kapton XC®: Morphology

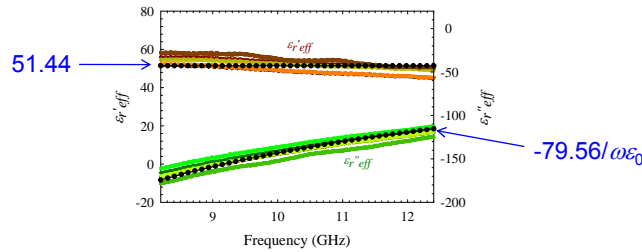
- ◆ Kapton XC is a non-homogeneous, carbon-loaded, polyimide film. **Surface roughness** is evident as well as **non-uniform carbon loading** throughout the cross-section of the ~40- μm thick film.



- ◆ Kapton XC is commercially available in a wide range of surface impedances and is very durable.
- ◆ We have also found in conjunction with previous studies that **small metallic patterns** can be accurately printed on the film's surface in order to modify its overall effective sheet impedance.

ϵ_r of Heat Treated Kapton XC[®]

- We measured five sheets of heat treated, 370 OPS Kapton XC. Then extracted the effective complex permittivity.

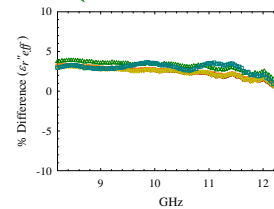
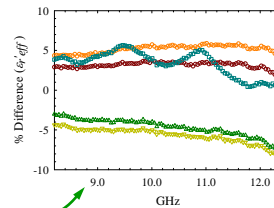


- Appreciable variation between sheets: a well-known property of Kapton XC. (Also known to be somewhat anisotropic.)
- A parallel RC model with $\epsilon_{r,eff} = 51.44 - j79.56/\omega\epsilon_0$ approximately describes the measured complex permittivity of Kapton XC within the X-band, though a more sophisticated model is likely necessary especially for broadband modeling.



Irreversible Temperature Effects on Kapton XC[®]

- Heating is required (~250 °C for 1 hr) to cure the direct-write "inks" used to print the metallic loops.
- The complex permittivity of carbon loaded polyimide is weakly sensitive to this necessary heating profile.
- Percent difference results for unheated vs. heated Kapton XC are informative.
- The real part of the permittivity either increases or decreases. However, in all cases the value of the imaginary part of the permittivity increases.
- These results are indicative of an increase in the number of electrically connected and closely spaced carbon particles in the heat treated film.



Outline

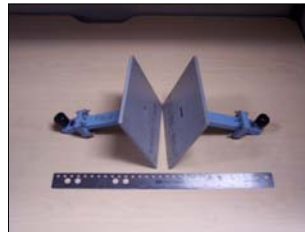
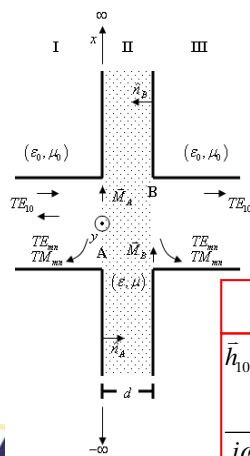
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Clamped Flange Waveguide Measurement



All measurements in this work were performed using a nondestructive, clamped flange, X-band waveguide measurement method.



MFIE FORMULATION

$\vec{H}_{tang}(0^-) = \vec{H}_{tang}(0^+)$	$\vec{H}_{tang}(d^-) = \vec{H}_{tang}(d^+)$
$\vec{h}_{10} - \sum_m \sum_n \Gamma_{mn} \vec{h}_{mn} =$	$\sum_m \sum_n T_{mn} \vec{h}_{mn} =$
$\frac{1}{j\omega\mu\epsilon} (k^2 + \nabla_t \cdot \nabla_t) \vec{F}(x, y, 0)$	$\frac{1}{j\omega\mu\epsilon} (k^2 + \nabla_t \cdot \nabla_t) \vec{F}(x, y, d)$



Verification with FGM-125

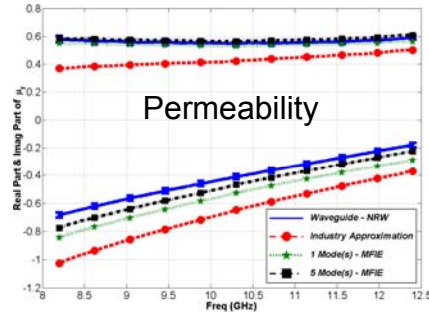
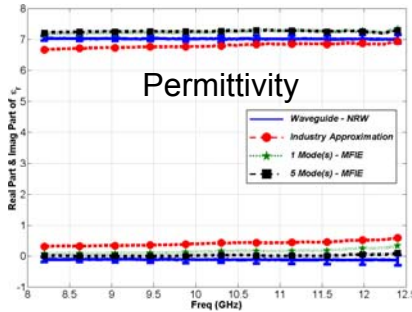


Used numerical root finding to solve the simultaneous set of equations relating to the magnitude of the thru and reflect S parameters:

$$\left| S_{11}^{thy}(\omega, \epsilon, \mu) - S_{11}^{meas}(\omega) \right| < \delta$$

$$\left| S_{21}^{thy}(\omega, \epsilon, \mu) - S_{21}^{meas}(\omega) \right| < \delta$$

ECCOSORB® FGM-125 magnetic material (~0.125" thick).



(M. W. Hyde IV and M. J. Havrilla, "A nondestructive technique for determining complex permittivity and permeability of magnetic sheet materials using two flanged rectangular waveguides," *Progress in Electromagnetics Research*, vol. PIER 79, pp. 367-386, 2008.)

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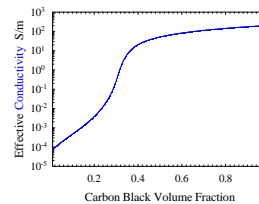
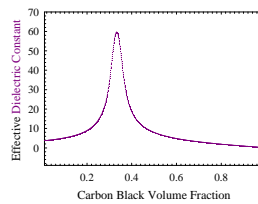
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Carbon Loaded Dielectrics

- ◆ Carbon loaded dielectrics such as Kapton XC possess complex permittivity (dielectric constant and conductivity) that are functions of the carbon loading.
- ◆ For spherical carbon particles in a dielectric host, K. T. Chung *et al.* (*J. Applied Physics*, Oct. 1982) report:
 - Bruggeman effective media formula accurately predicts the complex conductivity.
 - A volume fraction of carbon inclusions **near 0.33 (percolation)** achieves a **high effective dielectric constant** and **moderate effective conductivity**.
 - Higher volume fractions (greater than 0.33) of carbon inclusions are necessary to achieve **high effective conductivity**, but with low effective dielectric constant.

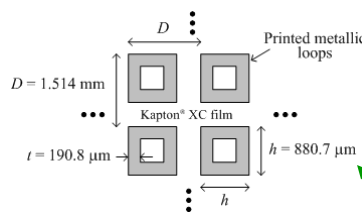
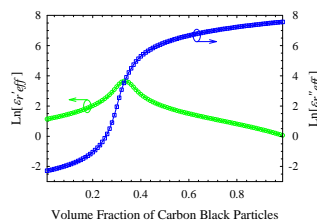


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Increase Both ϵ' and ϵ''

- Considering the case of carbon loaded dielectrics when the carbon loading exceeds the percolation threshold, it is observed that engineered gains in the dielectric loss with carbon loading reduce the film's dielectric constant.



- The central premise of this work is that **one can increase both the dielectric loss and the dielectric constant** of the carbon loaded film by printing electrically small particles on its surface.
- Our previous work has involved printing square pads as the small particle; however, in this study square loops are investigated.
- Square loop advantages include **consuming less metallic "ink" and decreased fabrication time** but still amenable to simple analytical modeling.

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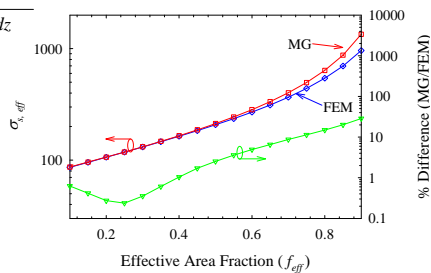
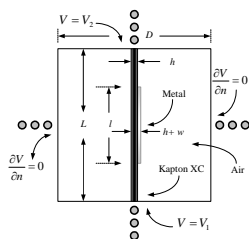


Maxwell Garnett (MG) Modeling

- Static finite element modeling (with *FlexPDE*) showed that the effective properties of the film with square loops can be modeled approximately using the **2D Maxwell Garnett (MG)** formula at least up to an effective area fraction for the metallic loops of $f_{eff} \approx 0.4$:

$$\nabla \cdot [\sigma \nabla V] = \nabla \cdot \vec{J} = 0$$

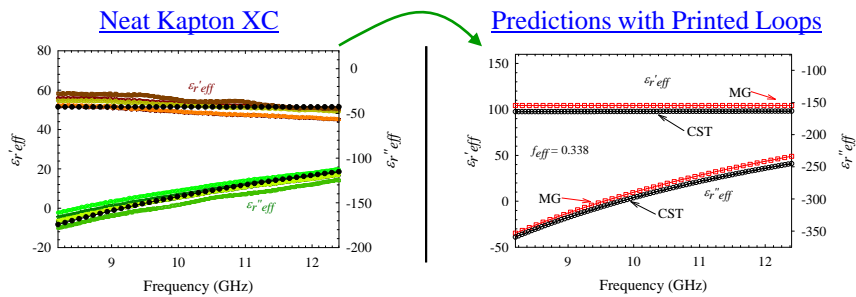
$$\sigma_{Unit Cell} = \frac{\int_{Vol.} \vec{J}_{(x,y,z)} \cdot \vec{J}_{(x,y,z)} dx dy dz}{\int_{Vol.} \vec{E}_{eff} \cdot \vec{E}_{eff} dx dy dz}$$



- In our previous work, observed even better agreement with solid square pads over nearly the entire range of area fraction.

X Band Maxwell Garnett Accuracy

- Then using the averaged film permittivity $\epsilon_{r,eff} = 51.44 - j79.56/\omega\epsilon_0$ in conjunction with the full-wave solver *CST Microwave Studio*, we tested the predictive capability of the 2D MG formula within the X band for our specific square loop geometry with $f_{eff} = 0.338$.



- We conclude that the Maxwell Garnett formula also works very well in the X band as a predictive tool for modeling the effects of printed square loop particles on R card.



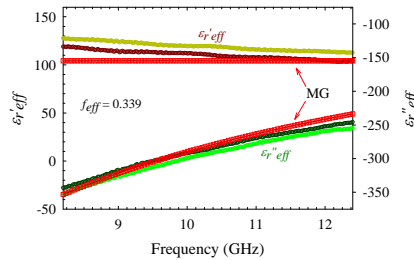
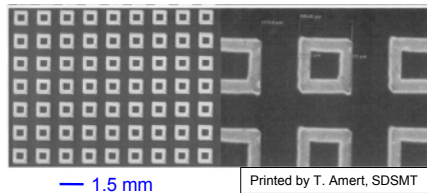
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Measured Engineered R Card

- We have also **experimentally investigated** the use of these methods to predict the complex permittivity of engineered Kapton XC films.
- Two sheets of engineered R card were created by printing metallic square loops at an effective area fraction of 33.9% onto 370-OPS Kapton XC, then heat treating.
- Comparison with the 2D MG effective permittivity for the engineered sheet shown on the previous slide [using the simple conductivity model $\epsilon_{r,eff} = 51.44 - j79.56/\omega\epsilon_0$]:



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Commixture: Hybrid-Mixture Films

- From the proceeding results it is evident that the complex permittivity of Kapton XC may be engineered with sufficient ease and accuracy with electrically small metallic square loops and the 2D MG formula subject to certain considerations.
- Perhaps of greater interest is simply a **generic carbon-loaded film** composed of a Bruggeman type effective media above the percolation threshold together with **small metallic loops** on the film's surface.
- The model for the complex permittivity of such a film is a combination of the Bruggeman and MG formulas, forming a **hybrid-mixture film**:

Carbon loaded film (3-D symmetric Bruggeman): $(1 - f_c) \frac{\epsilon_e - \epsilon_{eff,EMA}}{\epsilon_e + 2\epsilon_{eff,EMA}} + f_c \frac{\epsilon_c - \epsilon_{eff,EMA}}{\epsilon_c + 2\epsilon_{eff,EMA}} = 0$
 f_c = carbon loading volume fraction



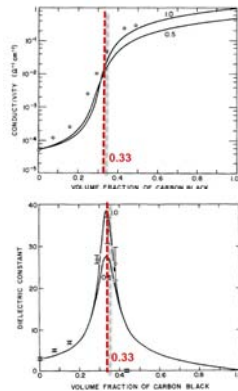
With small metallic loops (2-D Maxwell Garnett):
 f_{eff} = printed particle area fraction

$$\frac{\epsilon_{eff,MG} - \epsilon_{eff,EMA}}{\epsilon_{eff,MG} + \epsilon_{eff,EMA}} = f_{eff} \frac{\epsilon_{loop} - \epsilon_{eff,EMA}}{\epsilon_{loop} + \epsilon_{eff,EMA}} = 0$$



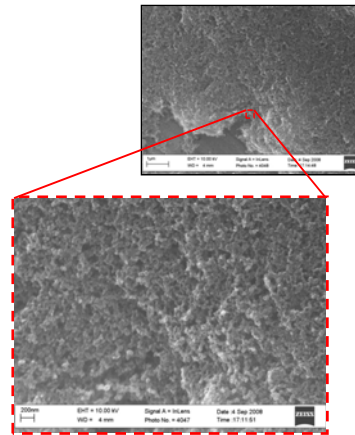
Nearly Ideal Bruggeman Material?

- ♦ Certain types of carbon loaded materials are known to behave as nearly ideal Bruggeman materials.
- ♦ SRF-S carbon black in PVC is an example:



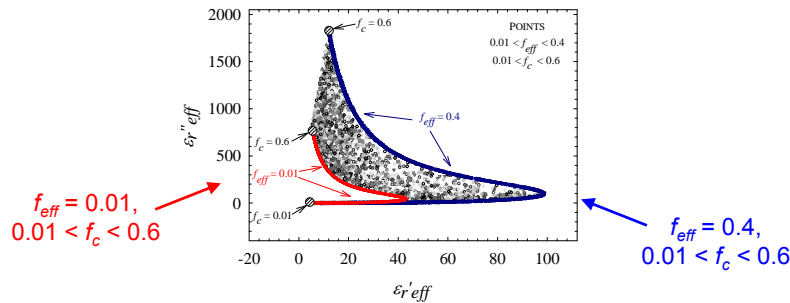
K. T. Chung, A. Sabo, and A. P. Piez, "Electrical permittivity and conductivity of carbon black-polyvinyl chloride composites," *Journal of Applied Physics*, vol. 53, pp. 6887-8879, Oct. 1982.

- ♦ SEM of Ketjen carbon black.
- ♦ Not an "ideal" Bruggeman behavior, but percolates at lower volume fraction.



Hybrid-Film Example

- A considerable range of possible complex permittivity values can be engineered for either a Bruggeman film or the specific Kapton XC considered in this study.
- Here a Maxwell Garnett-Bruggeman hybrid film is illustrated where f_{eff} (effective area fraction of printed square loops) ranges from 0.01-0.4 and f_c (carbon volume fraction) ranges from 0.01-0.6.



- Can **greatly increase** the space of $\epsilon_{r,eff}$ with printed particles.



Conclusions

- ✓ Overall quest of this work is to **produce lossy films with adjustable surface impedance**: Perhaps isotropic and uniform; perhaps spatially varying; perhaps anisotropic; etc.
- ✓ Presented measured complex permittivity results for heat treated Kapton XC using a flanged waveguide measurement method.
- ✓ Showed that the effective surface impedance of lossy films can be adjusted by **printing patterns of electrically small particles** on the surface. Accurately predicted by the **2-D Maxwell Garnett** formula.
- ✓ Further, with printed patterns can **simultaneously increase effective ϵ' and ϵ''** , which is not possible by changing only the carbon loading of the film.
- ✓ Introduced the **hybrid film** concept and showed the greatly enhanced space of effective ϵ' and ϵ'' available by varying both the carbon loading of the film and the area fraction of printed particles.





Thank You

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