Optimization of multilayered electromagnetic shielding using mesh adaptive direct search

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Purpose: To implement a method for designing the multilayered composite structures with user-defined shielding spectrums

Object: Multilayered composite structures, with layers composed of a polymer matrix with a conductive filler.

Methods:

- Waveguide spectroscopy to determine composite structure's reflection, transmission spectra
- Modified Mesh adaptive direct search (MADS) for mathematical optimization of the composite structures

Shielding properties calculation

$$\gamma_j = \frac{2\pi i}{\lambda}\sqrt{(\varepsilon'_j - i\varepsilon''_j)(\mu'_j - i\mu''_j) - (\lambda/2a)^2}$$ – layer propagation constant

$$Z_j = \frac{120\pi}{\sqrt{(\varepsilon'_j - i\varepsilon''_j)(\mu'_j - i\mu''_j) - \left(\frac{\lambda}{2a}\right)^2}}$$ – Input impedance of the sample layer

$$Z_0 = \frac{120\pi}{\sqrt{(\varepsilon'_c - i\varepsilon''_c)(\mu'_c - i\mu''_c) - \left(\frac{\lambda}{2a}\right)^2}}$$ – input impedance of the environment

$$X_j = \frac{Z_j(Z_j \tanh(\gamma_j d_j)) + X_{j-1}}{X_{j-1}\tanh(\gamma_n d_n) + Z_j}$$ – output impedance of the sample layer

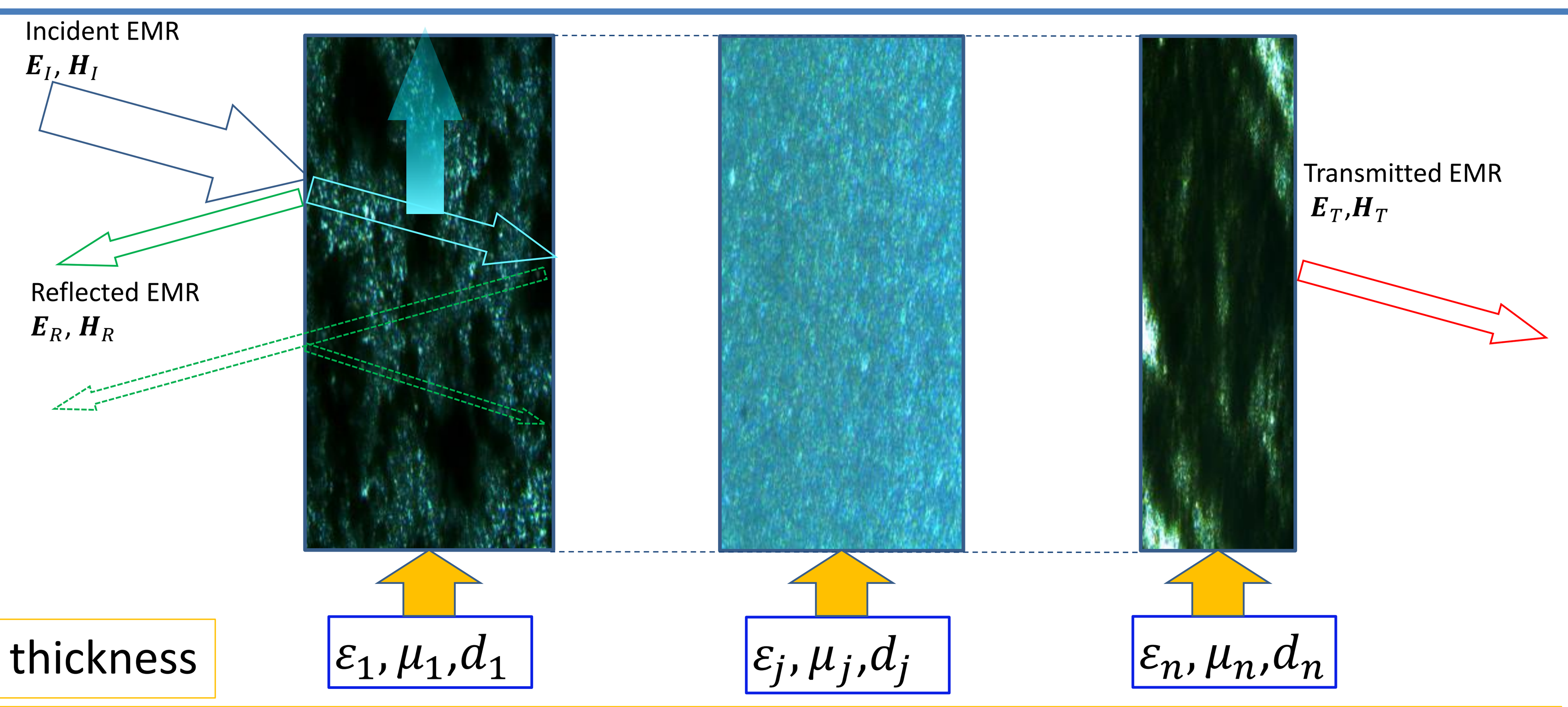
$$SE_T = 20\sum_{j=1}^{n+1} Log_{10}\left(Abs\left[\frac{X_{j-1}+Z_{j-1}}{X_{j-1}+Z_j}\right] e^{-\gamma_{j-1}d_{j-1}}\right)$$

$$T = 10^{\frac{SE_T}{10}}$$ – transmission index

$$RL = 10\,log_{10}(R) = 10\,log_{10}\left(Abs\left(\frac{X_n - Z_0}{X_n + Z_0}\right)^2\right)$$ – reflection loss

$$R = \frac{|E_T|}{|E_I|}$$

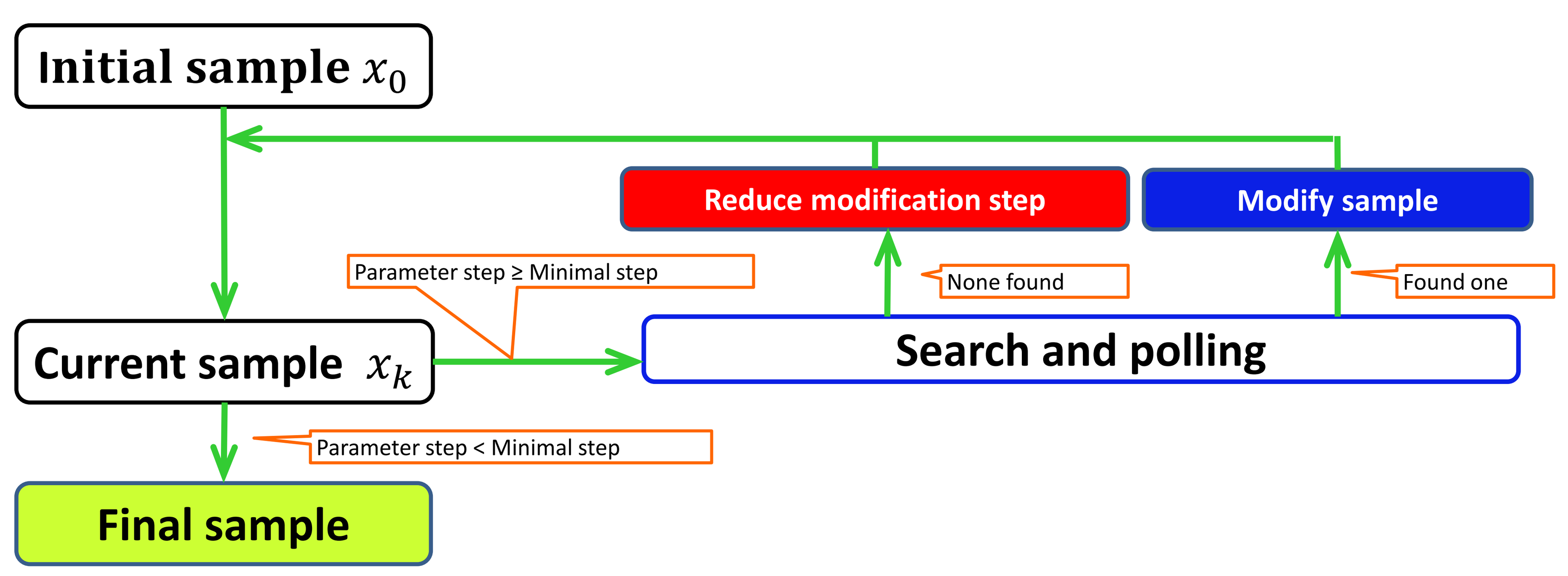
$$T = \frac{|E_R|}{|E_I|}$$



ε_j, μ_j depend on mass fraction of the conductive filler. The exact dependence can be modeled from experimental measurements and can be used in the optimization.

Mathematical optimization Mesh Adaptive Direct Search (MADS)[1]

General optimization algorithm



MADS algorithm

- Initialization: setting of $x_0 \in \Omega, \Delta_k^p \geq \Delta_k^m, D, k = 0$, objective function and constant parameters.
- Search and polling: are conducted until at least one point x_{k+1} in mesh M_k з $f_\Omega(x_{k+1}) < f_\Omega(x_k)$ is found. Calculation of f_Ω in P_k frame.
- Updating of parameters Δ_{k+1}^m and Δ_k^p. $k = k + 1$. Return to step «Search and polling».

x_0 – *initial sample (as a set of parameters)*

Ω – *parameter space*

$f_\Omega(x_k)$ – *objective function value in* x_k

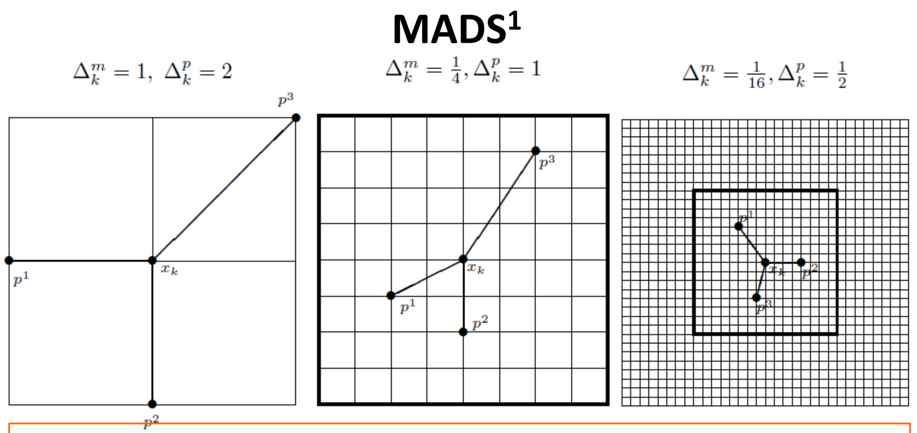
Δ_k^p – *mesh parameter during polling*

Δ_k^m – *mesh parameter during direction search*

$$M_k = \bigcup_{x \in S_k}\{x + \Delta_k^m Dz : z \in \mathbb{N}^{n_D}\}$$ – *parameter mesh at k iteration*

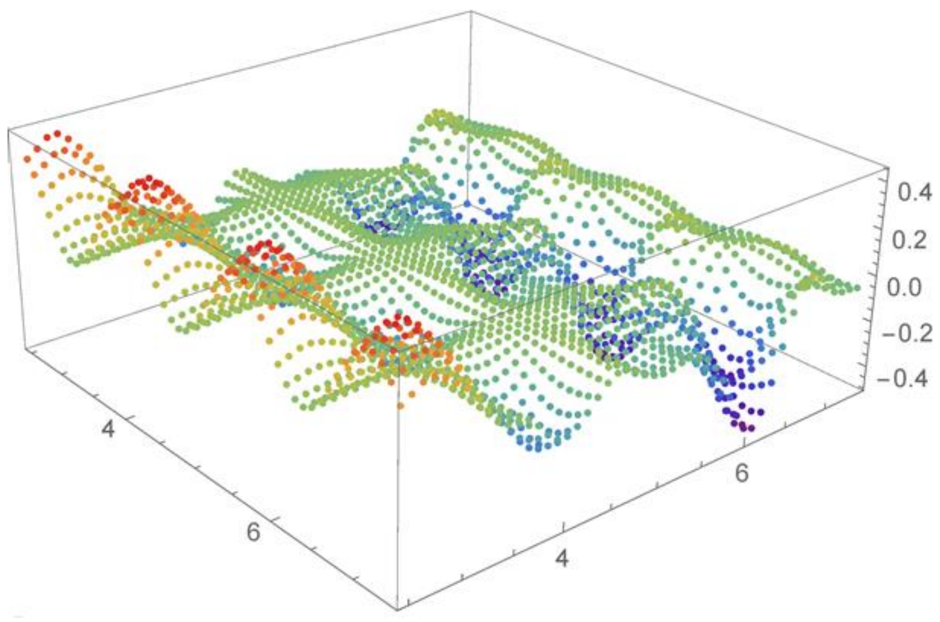
$$P_k = \{x_k + \Delta_k^m d : d \in D_k\} \subset M_k$$ – *tested points set around* x_k

M_k meshes with 2 parameters at k iteration of MADS[1]



Example of the mesh for single layer sample. The 2 parameters are conductive filler content and layer thickness. D consists of 8 directions $(d_1, d_2) \neq (0,0): d_1, d_2 \in \{-1,0,1\}$.

Example of objective function of 2 parameters



[1]Audet, C., & Dennis, J. E. (2006). Mesh Adaptive Direct Search Algorithms for Constrained Optimization. *SIAM Journal on Optimization, 17*(1), 188–217.

Optimization of the multilayered composite structures with conductive and dielectric fillers for predefined shielding spectrums

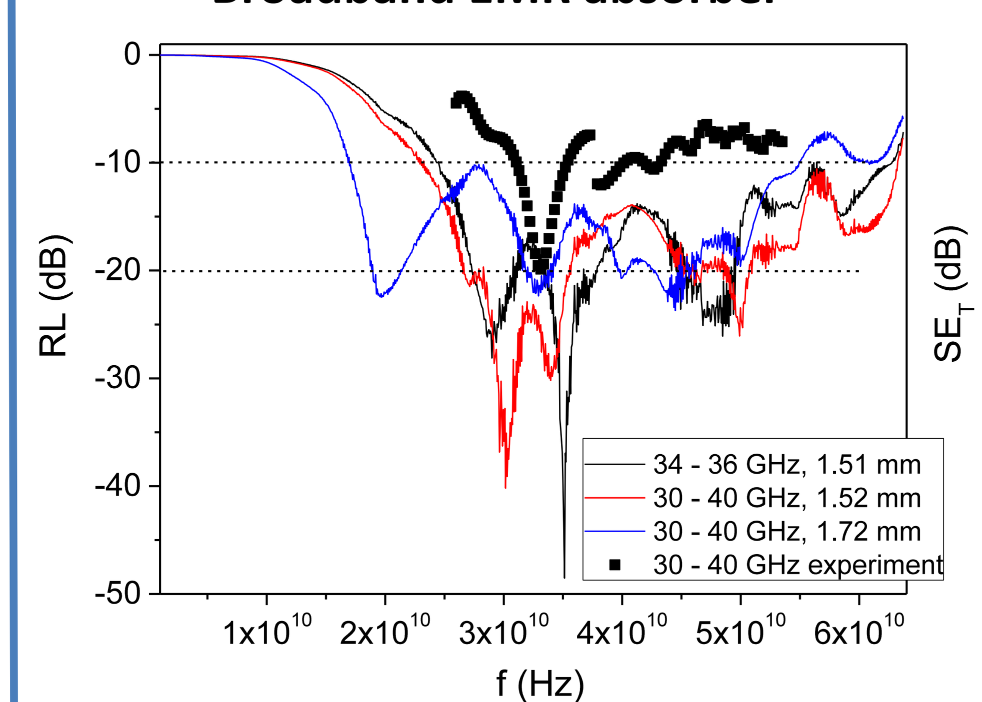
MADS has been used for the optimization of 3 types of composite structures:

- Narrow band absorber «34-36 GHz» (maximum EMR absorption (RL) at 34-36 GHz)
- Broadband absorber «30-40 GHz» (maximum EMR absorption at 30-40 GHz)
- EMR filter «30-40 GHz filter 1» i «30-40 GHz filter 2» (EMR attenuation at 30-34 GHz, EMR transmission at 35-40 GHz).

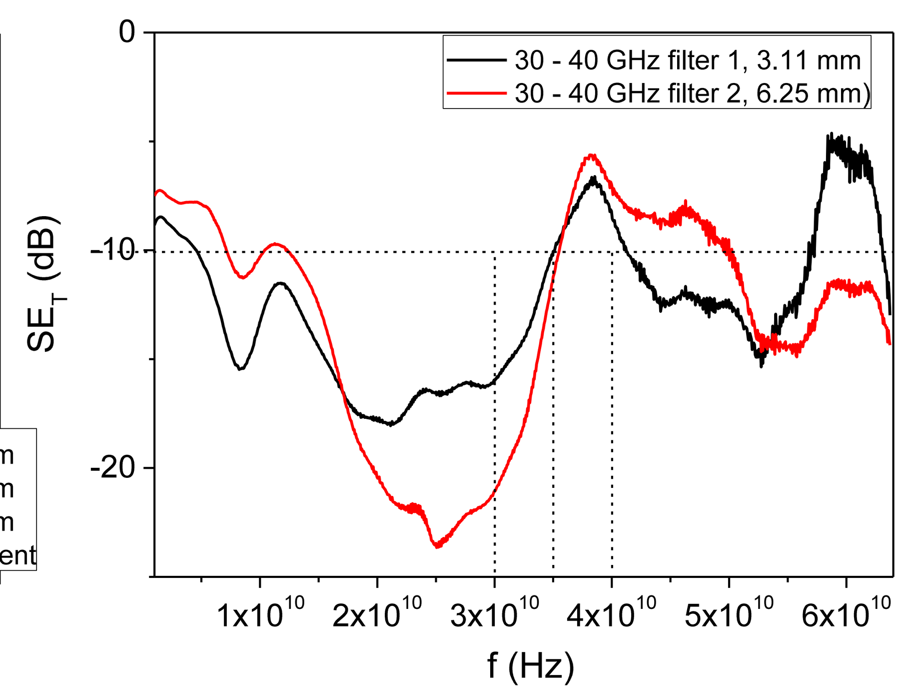
The composite structure «30-40 GHz» has been manufactured with the accuracy of each layer's thickness 0.05 mm. The blue line on the graph is an "innacurate" «30-40 GHz» sample, with it's layer's of the same composition but with thicknesses higher by 0.05 mm each.

Sample	Composition and thickness of the layers: CNT – carbon nanotubes, BT – $BaTiO_3$	d_Σ, mm
34-36 GHz	1 - 5% CNT+BT+L285, 0.1 mm 2 - 2% CNT+BT+L285, 0.02 mm 3 - 4% GNP+Fe+L285, 0.45 mm 4 - L285, 0.94 mm	1.51
30-40 GHz	1 - 5% CNT+BT+L285, 0.11 mm 2 - 4% GNP+Fe+L285, 0.28 mm 3 - 4% GNP+Fe+L285, 0.20 mm 4 - 1% CNT+BT+L285, 0.94 mm	1.52
30-40 GHz frequency filter 1	1 - 5% CNT+Fe+L285, 0.56 mm 2 - L285, 2.00 mm 3 - 5% CNT+Fe+L285, 0.56 mm	3.11
30-40 GHz frequency filter 2	1 - L285, 0.75 mm 2 - 5% CNT+Fe+L285, 0.46 mm 3 - L285, 2.02 mm 4 - 5% CNT+Fe+L285, 0.39 mm 5 - L285, 2.02 mm 6 - 5% GNP+BT+L285, 0.62 mm	6.25

Broadband EMR absorber



EMR filter



Conclusions

- MADS has been modified for the optimization of polymer-based composite multilayered structures for maximum EMR absorption. It has been tested by designing the EMR absorbers in 10 GHz band, 2 GHz band, and by designing the EMR filter in frequency range 30-40 GHz. The RL peaks of up to -48 dB, and EMR absorption bands up to 40 GHz with RL <-10 dB were obtained with total structure thickness < 2 mm.
- The RL and SE_T spectrums are sensitive to deviations of composite structure parameters. While the band widths with RL <-10 dB and EMR filters are less affected, the particularly deep absorption bands ($RL < -30$ dB) require high precision manufacturing of the multilayered structures. This allows it to design the multilayered composite structures for specific EMR shielding purposes.