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Hybrid Genetic Programming-Based Comparative Design of Broadband Metamaterial Absorbers using Graphene, Resistive Sheets, and Carbon Fiber

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***Abstract*—Hybrid genetic programming (HGP) is proposed to create new design topologies in the lower gigahertz frequency with new materials such as graphene, resistive sheet, and carbon fiber. HGP can create new topologies optimized per input parameters, such as low frequency and high broadband absorptivity. These designs are built and simulated in Ansys High-Frequency Simulation Software (HFSS) and evaluated by HGP. Graphene, resistive sheet, and carbon fiber patterning are explored and implemented with HGP to create low-gigahertz frequency and high-absorptivity MMAs. The graphene, resistive sheet, and carbon fiber-based patterned designs achieved 80% bandwidth above 80% absorptivity from 4.6 to 11 GHz, up to 15 GHz, from 3.83 to 9.13 GHz, and from 3.77 to 10.28 GHz, respectively.**

I. Introduction

Metamaterials are artificial materials that possess properties otherwise not found in nature. Metamaterials typically consist of subwavelength periodic structural unit cells. Typical metamaterial absorbers (MMA) consist of a metal-dielectric-metal design, where the top layer is a metal pattern and the bottom layer is a metal backplate. These designs create resonating structures that increase the electric field at the surface and have discrete high narrow absorption peaks [1].

Metallic-based patterned MMAs rely on the resonance of the pattern. These designs create unstable surface impedances at broadband frequencies, leading to narrow bandwidths. The metal pattern can be replaced by tunable material to create a relatively stable surface impedance [2]. Graphene is greatly sought for its excellent electrical properties, and conductivity tunability [3]. Resistive sheets come in all shapes and sizes, and resistive values to use to create a stable impedance surface for broadband performance. Carbon fibers layered in alternating orientations to mitigate anisotropic electrical properties [4]. This summary presents hybrid genetic programming to create designs using graphene, resistive sheets, and carbon fiber to achieve broadband performance.

II. Hybrid Genetic Programming

Hybrid genetic programming (HPG) is a combination of genetic programming (GP) with a low-level genetic algorithm (GA) optimizer. GP is utilized to create new design topologies and optimize design parameters. The low-level GA optimizer is used to improve the optimization efficiency of the design parameters. GP is a biological evolution-inspired algorithm where genetic operations are applied to a population over generations to design new topologies with high-performance characteristics. GP creates an initial population of designs and will evaluate this population's performance through a fitness function. Genetic-based operations are applied to the best-performing designs and will create the next set of populations of designs. The genetic-based operations are crossover, mutation, and elitism. Crossover mixes the design parameters of two members to create a new member, and mutation randomly changes one of the design parameter values to create a new member. Elitism pass along the best-performing member to the next population. The fitness function for absorption follows absorptivity, A, the fraction of the amount of incident electromagnetic waves absorbed by the surface. Where A is:

$$A = 1 - |S_{11}|^2 - |S_{21}|^2 \quad (1)$$

Where S_{11} and S_{21} are the reflectivity and transmissivity, respectively, the reflectivity is defined by the magnitude squared of the reflection coefficient, the S_{11} parameter, and the transmissivity is defined by the magnitude squared of the transmission coefficient, the S_{21} parameter. Although the designs have a metallic backplane, the S_{21} parameter is from the floquet port used in the full-wave simulations. The inclusion of the S_{21} parameter is to exclude any designs that have cross-polarization.

III. Patterned Materials

HGP was used together with Ansys High-Frequency Simulation Software (HFSS) to create broadband design metamaterials. Three approaches were used to create these broadband metamaterial designs.

A. Graphene

The first approach is the use of laser-induced graphene (LIG). The conductivity of LIG was modeled by the Kubo, which calculates the conductivity of graphene-based on an external bias electric field [5]. There are three designs optimized at varying electric field bias, 0 V/nm, 0.5 V/nm, and 4 V/nm. The respective conductivity of each design is 27.2 S/m, 387.9 S/m, and 1101.2 S/m. GP was able to create designs optimized for each conductivity value of graphene.

B. Resistive Sheets

The second approach is the use of resistive sheets of different sheet resistances. Resistive sheets are commercially available to obtain at varying sheet resistances. The patterned design optimized in GP to the sheet resistance of 100 $\Omega/\square$.

C. Carbon Fiber

The third approach uses quasi-isotropic carbon fiber (QICF) sheets. A novel GA-based method to measure the complex permittivity of thin samples was used to characterize the complex permittivity of the carbon fiber sheets [6]. With the complex permittivity of the QICF sheets, the impedance of the carbon fiber sheets can be calculated using boundary conditions between air and the carbon fiber sheet. The relative permittivity of the QICF sheet is ϵ_r = 13 and loss tangent, tan δ_e = 0.08. The complex impedance is calculated to be 104.24 + i4.16 Ω/□. The patterned design is optimized in HGP to the complex impedance of the QICF modeled as sheet impedance.

IV. Designs

The HGP-optimized MMA designs are illustrated in Fig. 1. The graphene-based patterning consists of a graphene pattern on top of polyimide, dielectric constant, $\epsilon_r = 3.5$, and the loss tangent, tan $\delta_e = 0.0026$. The resistive sheet and carbon fiber-based patterning consist of the respective material patterned on FR4, dielectric constant, ϵ = 3-4, and loss tangent, tan δ_e = 0-0.005. All designs come with copper backing. Table 1 lists the dimensions for each of the HGP designs.

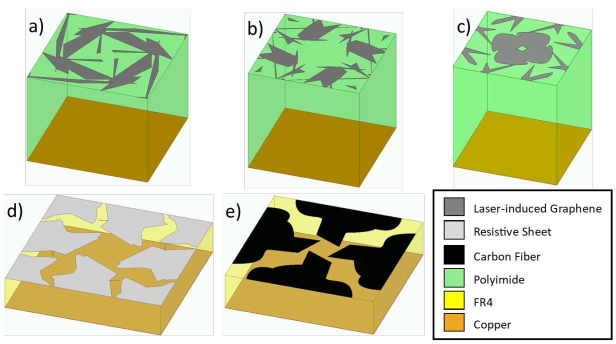

Fig. 1. Broadband metamaterial designs, a) 0 V/nm, b) 0.5 V/nm, c) 4 V/nm, d) 100 Ω/□, e) 104.23 + j4.16 Ω/□

TABLE I
Unit Cell Dimensions for Designs

Designs	Unit cell XY (mm)	Unit cell height (mm)
0 V/nm	6.65	5.17
0.5 V/nm	4.15	3.94
4 V/nm	3.5	1.63
100 Ω/□	23.37	4.94
104.23 + j4.16 Ω/□	20.00	4.93

V. Results

The absorptivity of all designs is shown in Fig. 2, and Table II shows the performance of each design above 80% absorptivity. The designs with patterned material aside from copper achieved above 80% bandwidth and above 80% absorptivity. From the LIG designs, it is observed that the bandwidth of the performance increased by increasing the electric field bias. The band structure of the patterned patterned resistive sheet and QICF is quite similar, with the carbon fiber performing slightly better.

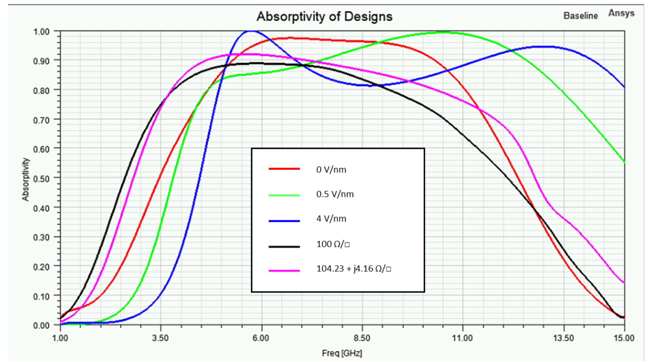

Fig. 2. Absorptivity of designs

TABLE II
Performance of Designs Above 80% Absorptivity

Designs	f_{min} (GHz)	f_{max} (GHz)	Bandwidth
0 V/nm	4.6	11	82.05%
0.5 V/nm	4.6	13.39	97.72%
4 V/nm	4.94	15	100.9%
100 Ω/□	3.83	9.13	81.7%
104.23 + j4.16 Ω/□	3.77	10.28	92.67%

VI. Conclusion

Five designs were created with HGP to demonstrate achieving broadband performance. Three graphene-based absorbers from different conductivity designs based on 0, 0.5, and 4 V/nm, one with resistive sheet-based patterning and one with QICF patterning, were designed, and simulated results were presented. The material-based patterned designs achieved 80% bandwidth above 80% absorptivity within the low gigahertz frequency. Future developments may include experimental verification by fabricating and testing designs.

References

[1] A. Li, S. Singh, and D. Sievenpiper, "Metasurfaces and their applications," *Nanophotonics*, vol. 7, no. 6, pp. 989–1011, Jun. 2018. [Online]. Available: https://www.degruyter.com/document/doi/10.1515/nanoph-2017-0120/html

[2] Y. Yang, Y. Song, and S. Fan, "Design of a metamaterial absorber based on resistive film structure," *AIP Conference Proceedings*, vol. 1971, no. 1, p. 020008, 2018. [Online]. Available: https://aip.scitation.org/doi/abs/10.1063/1.5041103

[3] "Graphene Synthesis, Properties, And Applications – Cheap Tubes." [Online]. Available: https://www.cheaptubes.com/graphene-synthesis-properties-and-applications/

[4] Q. Zhao, K. Zhang, S. Zhu, H. Xu, D. Cao, L. Zhao, R. Zhang, and W. Yin, "Review on the Electrical Resistance/Conductivity of Carbon Fiber Reinforced Polymer," *Applied Sciences*, vol. 9, no. 11, p. 2390, Jan. 2019. [Online]. Available: https://www.mdpi.com/2076-3417/9/11/2390

[5] G. W. Hanson, "Dyadic green's functions for an anisotropic, non-local model of biased graphene," *IEEE Transactions on Antennas and Propagation*, vol. 56, no. 3, pp. 747–757, 2008.

[6] S. S. Zhang, M. F. Iskander, Z. Yun, E. Chong, X. Yuanzhang, M. Nakamura, J. J. Brown, and B. Jones, "A novel genetic algorithm based method for measuring complex permittivity of thin samples in the compact radar frequency band," in *2023 United States National Committee of URSI National Radio Science Meeting (USNC-URSI NRSM)*, 2023.