A Novel Encoding Strategy of Enhanced Broadband and Absorption Conformable Metamaterial for MW Applications

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ABSTRACT

Analog metamaterials (MMs) manipulate their effective medium parameters with difficulty, when their geometric architecture is composed of hybrid compositions. However, genetic algorithms, calculation-analog search algorithms that seek for optimal solutions, can be applied to artificial metamaterial-architecture construction. This paper proposes a novel encoding strategy for metamaterial architecture construction that utilizes multi-parameter extremum-seeking optimization. The binary encoding and decoding of the geometric-layer thickness enables the form’s final dimension to be based on the objective fitness function. The genetic algorithm iteratively optimizes the initial geometrical dielectric-layer thicknesses. Then, combining the initial optimized parameter with the composite-metal multi-loops’ spatial distribution, the final metamaterials were analyzed using numerical analysis software. Based on a co-simulation disposition, the proposed metamaterial exhibits 2.5-GHz broadband features with over 80% physical absorption of spatial waves. The proposed metamaterial simultaneously presents low radar cross-sections, wide polarization insensitivity, and dynamical flexibility. Moreover, the proposed metamaterial, when loaded onto a reference antenna, exhibited good real application capability in radar cross-section reduction for physical passive-equipment invisibility. The numerical-simulation and experimental results of the MM’s absorption and flexibility properties showed good agreement, suggesting the advantage of genetic-algorithm optimization co-simulated with numerical-analysis software for metamaterial architecture construction. It shows good potential application for complicated spatial-geometry formations.

INDEX TERMS

Genetic algorithm, metamaterials, broadband, high-absorption, radar cross-scattering reduction.

I. INTRODUCTION

Metamaterials (MMs) are artificial materials engineered to have many uncommon properties; hence, they have always been a pervasive research topic of interest in optics [1]–[3], electronics [4]–[6], machinery [7]–[9], and even acoustics [10]. Developments in these disciplines concentrate on special characteristics or functionalities [11]–[13], e.g., surface or spatial wave control [14]–[16], bandwidth enhancement [17]–[19], radar-scattering distribution reduction [20]–[23], and electromagnetic (EM) shielding [24].

Anomalous MM characteristics are always attributed to deliberate architectures, due to random material collocation and spatial-architecture construction. However, previously investigated approaches to spatial-architecture constructions usually lack sufficient focus on a simple, sequential, fast, and low-cost strategy. Recently, an encoding method for MM design has provided a promising avenue for engineering desired structures [25], [26].

MMs with excellent properties and multi-functionality are directly reorganized and established, whether the surface lattice is encoded with a binary sequential code [26], [27] or a special structure is redefined by targeting the refection phase [28]. Having evolved from analog MMs with periodic
particle arrangements, encoded MMs aim to achieve excellent functionality by restructuring the objective function, which provides the final optimization goals for the design.

Genetic algorithms (GAs) possess many properties, e.g., tunability, robustness, and maturity [29], [30] in multi-objective solutions, and have frequently been used for complex goal dispositions [31], [32] to achieve parameter encoding. MM optimization involves dynamically modulating reasonable parameter codes, according to the objective function. The MM’s functional requirements and architecture can be guaranteed and modeled, based on optimal code sequences of different parameters or structures.

With MMs’ gradient merits, scholars have always tried to improve bandwidth and absorption peaks in radio frequency (RF) or microwave (MW) applications, owing to MMs’ great enhancement of signal capacity and stability [33], [34]. Currently, a large number of studies have focused on two challenges:

1) Stacking composite structures [35], [36], using strong magnetic materials [37], [38], and combining interfacial resistance materials [39], multi-time resonances [40], [41], and simple unit-structure designs [42] to widen the working band;

2) Constructing fierce LC resonances [43] and increasing dielectric or metal losses [44] to enhance electromagnetic (EM)-wave absorption.

Although these methods can promote MMs’ applied features, optimal results can be unreliable and the experimental process is independent, even when many false absorptions occur, due to EM-wave polarization transformations [45]–[50]. If one relies on analog metamaterials and a continuous-size design, the aforementioned design process is complicated and tedious. Thus, encoding artificial MMs is a sound strategy, which provides a precise architecture-construction strategy and alleviates the burden of conventionally simulating complex designs, and global multi-parameter optimization. By co-calculating and experimenting with commercial software and optimized code sequences, an encoded structure can be constructed to meet complicated goals.

In this paper, a novel encoding strategy utilizing a GA to form a broadband and high-absorption MM is proposed. The GA optimizes the initial geometrical-layer thicknesses and enables a co-simulation between the CST electromagnetic-field simulation software and MATLAB, by connecting code servers with parameters, as the foundation of the MM structure. The binary encoding and decoding of the geometrical-layer thickness enables the final form dimension to be based on the objective fitness function.

After periodically paralleling the multi-loop surface profile engineered in CST, the architecture was constructed using the initial layer thickness and arrangements in the spatial metal. The final presented MM shows excellent properties, e.g., broadband capability, polarization-independent, a low radar cross-scattering (RCS) level, and high flexibility.

II. PRINCIPLE AND METHODS
A. COMPOSITE-METAMATERIAL CHARACTERIZATION

Knowing the relationship between an MM’s functionalities and architecture parameters is a precondition for tailoring continuous code using GA optimization. For multi-layer metamaterials, the correlations between layer thicknesses, bandwidths, and absorptions should be considered first. The composite-substrate thickness determines the device flexibility.

According to transmission-line theory, the MM’s reflection coefficients can be represented by Eq. (1), when the incident wave propagates vertically to the structure surface. The dielectric loss, due to the different transmission rates of EM waves within the different materials, is the key to attenuating the incident energy for multi-layer metamaterials. The thickness and impedance of the different substrates mainly influence the control of the final absorbent energy.

The correlation between the equivalent impedance \(Z_n\) and the thickness \(t_n\) of the \(n\)th layer materials can be described by Eq. (2):

\[
RC = \left| \frac{Z_n - Z_0}{Z_n + Z_0} \right|,
\]

\[
Z_n = Z_{n-1} + \eta_n \tanh(\gamma_n t_n)
\]

\[
\eta_n = \sqrt{\frac{\epsilon_n}{\mu_n}} \gamma_n = \frac{2\pi f}{c} \sqrt{\frac{\epsilon_n \mu_n}{c}}.
\]

where \(Z_0\) is the free spatial impedance, 377 \(\Omega\); \(c\) is the transmission rate of EM waves in vacuum; \(f\) is the center frequency in the working band; and \(\epsilon_n\) and \(\mu_n\) are the complex permittivity and permeability of the \(n\)th layered material, respectively. The absorption level of an MM can be represented as \(A(\omega) = 1 - R(\omega) - T(\omega)\), where \(R(\omega)\) and \(T(\omega)\) are the reflectivity and transmittance of the EM wave, respectively. \(T(\omega)\) is close to zero when the back of the MM is almost-foil metal, so the absorption is related only to the reflection coefficients.

To obtain the optimal absorbent bandwidth and rate, the layer thickness, as an initial variable, should be coded first. Here, the substrate thickness value is represented by \(S\)-bit binary coding, and the maximum thickness \(t_{\text{max}}\) of each layer is only 1 mm. The process of encoding and decoding a multi-layer MM’s thicknesses is shown in Fig. 1.(a). The relation is the maximum layer thickness to the corresponding parameter-value precision is as follows:

\[
2^{s-1} < \frac{t_{\text{max}}}{\phi_t} < 2^s,
\]

where \(\phi_t\) is the thickness precision in the design process, defined as 0.001, so a single parameter value can be depicted as a 10-bit code.

B. OBJECTIVE FUNCTION DEFINITION AND GA ENCODING PROCESS

The initial optimizations of MM bandwidths and absorption rate is higher than 90%. The objective function should link the
absorptivity ($\text{A} = 1 - \text{RC}$, where the backplate is pure metal) with the bandwidth, and their calculations must have identical optimizing weight coefficients. From here, the defined fitness function is as follows:

$$f_u = 1 - \frac{\sum_{i=1}^{n} (f_{i\text{max}} - f_{i\text{min}})}{f_{\text{max}} - f_{\text{min}}} - \text{RC},$$

(5)

absorptions are a multi-objective optimization problem. To obtain a higher absorption and a wider working bandwidth, the return loss should always be lower than $-10$ dB, if the where $f_{i\text{max}}$ and $f_{i\text{min}}$ are respectively the maximal and minimal frequencies in the $i^{th}$ working band when $\text{A} > 90\%$; $f_{\text{max}}$ and $f_{\text{min}}$ are the upper and lower limit frequencies, respectively. Here, the minimum level of the fitness function should be pursued through GA dispositions.

Herein, the substrate-layer thickness is regarded as the major calculation factor for GA optimization, which is closely related to the fact that the material permittivity and permeability affect the goal function. First, the materials are selected. Two RF materials, flame-retardant 4 (FR4) and the Rogers RT5880 high-frequency laminate, are suitable for electronic-loss reduction in many RF devices, e.g., antennas, couplers, and absorbers. In addition, ultra-thin materials can be bent around a curved surface, owing to their favorable mechanical properties. In addition, polydimethylsiloxane (PDMS), as a middle sticky layer, not only connects the top and bottom substrates, but also acts as a flexible dielectric material.

Second, once the substrate materials are chosen, the main function of the objective achievement is to iterate in a loop. The boundary condition is given by Eq. (4). The main function iterates four times, corresponding to the four substrate layers. By invoking the GA tool in MATLAB, the objective function, as the fitness function, is calculated to obtain the final optimized code. Finally, by linking the interfaces of CST and MATLAB, we establish an interaction between them. The main part of the real coded genetic algorithm was programmed by MATLAB, and the model calculation was completed by CST.

Fig. 1(b) shows the GA-operation flowchart of the MM optimization. The GA program creates a sequence of initial chromosomes to tune the EM code for each layer, which aims to calculate the final optimized layer thickness. The best absorption and a wider bandwidth were obtained by optimizing the fitness function.

In the calculation, the initial population was set to 20 in the generation. Two elite individuals in the tournament selection were regarded as the initial individual; the other initial individuals were created using random functions. The crossover probability was set to 0.8, the mutation rate was set to 0.01, and a maximum generation number of 60 sets was the stop condition.

The modified parameters were obtained after 60 iterative evolutions, and the optimal MM architecture with a four-layer dielectric was not only bendable but also enhanced the electric loss between different substrates;
therefore, all parameters were represented as 40-bit codes.

III. EXPERIMENT AND DISCUSSION

A. GA-OPTIMIZATION RESULTS

As shown in Fig. 1.(c), the low fitness level indicates a higher EM-wave absorption and a wider working bandwidth. Fig.1.(d) shows the final optimized dielectric-layer thicknesses. The initial layer-thickness parameters can be characterized when the final calculation of the best individuals is completed. Based on the initial thickness value, the clear MM formation, combining the optimized four layers with the special metal-structure distributions, is further investigated using full-wave analyses in CST. The detailed structure configurations are described next.

B. STRUCTURE CONFIGURATIONS AND PHYSICAL SAMPLE MEASUREMENTS

MMs with stable performance under various incident angles and different polarizations are widely desired in many fields; here, we only focus on the of center-symmetry structures, targeting the excellent performance of the MM. Applying the initial layered thickness, generated by the GA optimization, a numerical EM calculation utilizing the finite-different time-domain (FDTD) method is conducted to analyze the infinite planar MM array, composed of a uniform cell with a periodic configuration. The Floquet boundary and excitations are also managed to become a linear periodic working in isolation, as shown in Fig. 2. (a). This generates full-architecture representations of the metamaterial planar array out of one cell. The electric direction of the incident planar wave parallels the x-axis of the coordinate system.

In terms of the aforementioned layer-thickness parameters, one independent cell is comprised of a back metal layer of full copper foil ($\sigma = 5.88e + 07$/m), an insulator layer of Rogers 5880 (Ro5880, $\varepsilon = 2.2$, $\tan\delta = 0.0009$), a five-metal resonant square-loop (Q-loop) array, a flexible adhesive layer of PDMS ($\varepsilon = 2.75$, $\tan\delta = 0.03$), a sputtered aluminum plate layer (Al, $\sigma = 3.56e + 07$/m), a PDMS layer, a flame-retardant 4 layer (FR4, $\varepsilon = 4.4$, $\tan\delta = 0.02$), and a Q-loop array layer, structurally arranged from the bottom to the top, as shown in Fig. 2(c). The spacing and dimensions of the two Q-loops maintain their spatial counterparts in the dielectric plate, and the wire width of the five Q-loop array has a periodic sequence between two sizes ($w_1$ and $w_2$), as shown in Fig. 2(b) and (d). The dimensions of each part of the unit cell are illustrated in Table 1.

Metal Q-loop arrays on the top and bottom insulator substrate were etched with high-density interconnector technology, because their scale is on the order of microns. The three interconnections of the plane between the different dielectrics are integrated in multiple layers using cationic bonding technology. The MM sample is fabricated using MEMS technology. The overall prototype consists of $15 \times 15$ cells of MM elements with a $12 \times 12$ cm$^2$ area, as shown in Fig. 2.(e) and (f). The fabricated sample demonstrates excellent bendability over a wide-angle range.

The free-space test method, shown in Fig. 2.(g), was applied to test the absorbing features, by vertically transmitting standard transverse electric (TE) or transverse magnetic (TM) beams from the incident horn antenna to the AM sample. The TE and TM modes are excited when the short edge and the long edge of the transmitting horn antenna are vertical to the ground. By modifying the position of the supporting tripod to adjust the incident angle, the different polarization and oblique-incident responses of the MM’s absorptivity were measured. An external network analyzer formulated the time-domain spectra in a Fourier transform from the transceiver and transmitter to obtain the absorptivity.

IV. RESULTS AND ANALYSES

A. TRANSMISSION AND REFLECTION COEFFICIENTS

After GA-based optimizations and the construction of the structure, the final MM presents many bandwidth and absorptivity advantages. Fig. 3 shows the numerical energy responses and the transmitting spectrum at a working band range of 5.5–12.5 GHz. Fig. 3.(a) shows that the power accepted by the entire geometry is more than 80%, at the band of 7.81–10.31 GHz. The power exiting through the two ports corresponds to the absorbed energy at the rated power of 5 W. The energy absorbed from the multi-dielectric and metal-structure losses was almost identical in the lower band; however, this was developed from the substrate losses in the higher band.

As observed in the reflection-coefficient characterizations, shown in Fig. 3.(b), the trends primarily keep pace with the absorbing energy transformation. The anisotropy of different materials at high frequencies leads to tight deviations. Moreover, RCs in the cross-polarization (cro-pol) direction converge nearly to zero, far below that in the co-polarization (co-pol) direction, which indicates that the EM wave was absorbed by the proposed MM, rather than the wave transformation.

In addition, the transformed intensity (720°) of the cross-polarized reflective phase is far greater than the co-pol level (−88.7°–64.0°), and the strongest changes in the co-pol phase difference mostly excite the endpoint of the working band, as shown in Fig. 3.(c). This longer delay of the reflected phase in the co-pol direction exhibits a small EM wave returning to the output port, which further verifies a definite absorption by the MM, instead of the polarized transformation.

The absorptivity of the proposed MM is shown in Fig. 3(d), when the TE and TM waves normally propagate to the proposed MM. The absorption in the TE and TM incident waves is almost uniform, and only a slight discrepancy is observed at 8.8 GHz because the electric-dipole absorption is stronger than the magnetic absorption of the multi-Q-loop structure. A valid absorption broadband of over 80% achieved nearly
TABLE 1. Detail architecture spacing dimensions of MMs cell as shown in Fig.2.

| Parameter | Value (mm) |
|-----------|------------|
| a         | 8          |
| l₁        | 5.02       |
| l₂        | 5.44       |
| l₃        | 5.61       |
| l₄        | 6.03       |
| l₅        | 6.2        |
| w₁        | 0.15       |
| w₂        | 0.4        |
| dₚ        | 7.37       |

2.4 GHz (7.8–10.2 GHz). The broadband responses attributed to the MM possess a good continuity of effective resonances to different Q-loops, and strong dielectric losses to the structural composite layer. Furthermore, the broadband feature complies with the ultra-wideband principle [41], which can be formulated as

\[ BW = \left( \frac{f_{\text{max}}(\text{abs} > 0.8) - f_{\text{min}}(\text{abs} > 0.8)}{f_c} \right) \geq 25\% \]

where \( f_c \) is the center frequency of the working band. The actual BW level of the proposed MM was 26.7%.

**B. BROADBAND PROPERTY VERIFICATION**

In the TE polarization mode, the electric-property representations, shown as E-field distributions in Fig. 4, can verify the broadband implementation derived from the complex resonances. The cell profiles of the E-field in the strongest electric position are shown in Figs. 4.(a)–(c), versus working frequencies of 8 GHz, 9 GHz, and 10 GHz. Three fierce electric configurations present a downward trend from the position of the superficial Q-loops, through the superficial Q-loops and upper FR4 layers, with increasing frequency.

According to the superficial E-field distribution shown in Fig. 4.(d)–(f), the strong resonant location gradually deviates from the outer to the inner loops, which bears out the negative correlation between the electric resonant path and the working frequency. The Q-loop bilateral metals develop bi-parallel capacitances with a strong electric distribution,
as the side potential is higher in the middle of each cell. This exhibits electrical resonances from the equivalent-capacitance response. The physical structural arrangement of sequential metal loops and the corresponding extended depth of the dielectric resonant locations facilitate the effective formation of the MM absorbent wideband.

To verify the broadband feature based on the GA optimization, different assemblies of the proposed MM, with a single layer or bilayer and the final MMs were tested in sequence, as shown in Fig. 4.(g). The single-layer material only shows one absorbent peak at a high frequency, while the bilayer MM without etching on the middle metal layer shows...
wideband absorption across a lower frequency. In contrast, the bandwidth improvement indicates the broadband feature, attributed to the interstratified dielectric loss and the parallel equivalent-capacitance attenuations, which are caused by the potential difference between the middle metal and the Q-loops.

Additionally, the absorbent mechanism can be illustrated by the equivalent circuit, which is built from a complex LC circuit, as shown in Fig. 4.(j). Each metal layer is depicted by multi-lumped components, and the dielectric layer contains a certain impedance. The equivalent input admittance of the circuit can be presented as $Y_{in} = Y_{fss} + Y_e$. $Y_{fss}$ and $Y_e$ are the equivalent admittances of the superficial metal and the bottom multi-layer architecture, respectively. The equivalent admittance can be represented as $Y = G + jB$, where $G$ is the electric conductance. When the electric susceptance ($B_e$) of the equivalent LC circuit is close to zero, the proposed structure can excite an effective resonance with only an impedance-characterization access to a perfect EM-wave absorption.

Using the equivalent-circuit inversion method, the electrical susceptance of the superficial metal and the bottom composite architecture are calculated as shown in Fig. 4.(j). The sum of the two electrical susceptances mainly maintains a level of zero along the high absorption wideband, which is numerically and theoretically in accordance with the MM’s absorbent performance in the wideband range.

C. POLARIZATION CORRELATIONS AND RCS DISTRIBUTION

The MM’s polarization is a key indicator for evaluating the tolerance that determines its EM-wave feature selectivity. Fig. 5.(a) shows the absorptivity of the proposed MM under a normalized polarized TE wave with different polarization angles. The obvious polarization-independent angle exhibits a favorable absorbance in the wideband range, while the MM

FIGURE 5. Polarization properties of the MM in TE mode. (a) absorbent response under the normalized polarized wave with different polarization angles; (b) absorbance characterization under oblique incident wave with different incident angles. Experimental results of the proposed MM in two incident mode. (c) measured and simulated absorption response in the incidence by TE and TM wave vertically; (d) measured data in a curving condition of the fabricated MM array when it is conformal with a foam cylinder of the radius of $r$. 
absorption over 80% is stable and high with the changes in the polarized angle in the band range of 7.65–10.38 GHz.

The small EM wave in the TE mode is absorbed with the increase of the oblique incident angle; however, an absorptivity greater than 60% is still achieved at 7.5–10.5 GHz when $\theta < 50^\circ$, as shown in Fig. 5.(b). The fractional bandwidth of the proposed MM absorber with over 80% absorption is 39%. For microwave devices, a relative bandwidth of over 25% can be defined as an ultra-bandwidth; hence, this proposed MM absorber is an ultra-bandwidth MM. Additionally, the absorbent responses in both incident modes remain at a high level over a wide incident-angle range, which adequately validates the polarization insensitivity of the proposed MM.

Additionally, the radar cross-scattering (RCS) of the general architecture implies a special invisibility level in fierce EM environments. Fig. 6 shows the MM’s RCS radiative distribution with a 15×15-cell component at working frequencies of 8, 9, and 10 GHz. It obviously exhibits a strong RCS level along the AM’s normal direction. As the unabsorbed EM wave along the normal direction is fully reflected by the MM, the other direction couples with a lower scattering wave. Moreover, the strongest levels, $-16.4$, $-13.4$, and $-12.8$ dB, for the three working frequencies, respectively, is lower than the $-10$-dB rating value in the EM-interference discipline.

The excellent RCS level illustrates that the proposed MM has good invisibility, which can be widely applied to radar applications. The most significant merit of our MM is the rational combination of its construction design with the GA optimization and superior broadband feature. This is higher than related work with similar periodical metamaterials, as shown in Table 2, where HPBW is the half-power bandwidth. In the comparison, our optimized MM possesses a wider bandwidth and an optimal incident-angle tolerance.

### D. EXPERIMENTAL VERIFICATION AND ARRAY-ANTENNA RCS REDUCTION

To verify the broadband-absorption validity, the physical absorptivity of the MM in real free-space experiments was measured. In the TE and TM modes, Fig. 5.(c) shows the experimental absorptivity, which strongly agrees with the simulation data. The difference between the practical and numerical results is attributed to errors in the MEMS manufacturing precision and the test process. Additionally, to verify the polarization sensitivity and flexibility of the proposed MM, the thin MM was wrapped around a foam cylinder with a radius of $r$ to test its bent absorptivity, as shown in Fig. 5.(d). When the radius of the cylinder decreased, the absorbent peak developed a slight right-shift of 23 MHz.

With high absorption and low RCS, the proposed MM shows great potential for passive-equipment invisibility. Here, the 6×5 planar-array antenna shown in Fig. 7.(a) is utilized for the RCS reduction of the proposed MM in monostation radar detection. As shown in Fig. 7.(b), the antenna
array parallels the MM, and the spacing between the reference array and the fabricated absorbent MM is three working wavelengths ($\lambda_0$ is the corresponding working frequency of 9 GHz). The ground plane of the MM was not removed while the test was conducted.

Fig. 7.(c) shows that both the numerical and experimental return losses (S11) below -10 dB at a resonant frequency of 9 GHz exhibited good impedance-matching performance. For the microstrip patch antenna, the coaxial probe used the high-frequency signal as the power input. The transmission quality of the RF signal will be reduced because a small deviation in the fabrication precision of the coaxial probe leads to a relatively larger error at high frequencies. Thus, the experimental resonant depth is lower than that of the simulation data.

Moreover, the impedance bandwidth of the coaxial connectors at high frequencies are wider than those at low frequencies, owing to the easy establishment of an impedance match between the coaxial probe and the patch antenna; hence, the experimental bandwidth is wider than the simulated data. The RCS distribution along the normal direction always maintains the highest level because the vertical section of the passive equipment is largest, relative to the transmitting radar.

The RCS distribution along the normal direction of the array antenna was tested by paralleling the disposition of the MM, as shown in Fig. 7.(d). After the MM was loaded onto the reference antenna, the RCS distribution was obviously reduced at the MM’s high-absorption band, which illustrates a positive correlation of the MM, between the RCS reduction and EM-wave absorption. The high RCS level in the low-frequency band caused the entire structure dimension to increase and the resonant size did not match the radar wave.

Finally, the radiation pattern of the reference-array antenna loaded with the proposed MM was tested at 8.5 and 9 GHz in the microwave chamber; the simulation patterns are shown in Figs. 7.(e) and (f), respectively. It can be observed that the array antenna still has a higher realized gain and lower side-lobe level after the proposed MM was loaded. The tested radiation pattern is in good agreement with the simulation data. Additionally, the radiation pattern is almost constant for the realized gain and the transforming trends at different frequency points. As evidenced by the RCS distribution applied to the array antenna, the proposed MM with high absorption contributes to the RCS reduction in passive equipment and shows its potential value for EM-interference invisibility.

V. CONCLUSION

This paper presented a novel encoding strategy for metamaterial-architecture construction by means of genetic-algorithm multi-parameter optimization. Multi-objective function operations obtained geometrical-layer–thickness parameters in relationship with both the broadband and reflection coefficients. Digital binary encoding and decoding of the geometrical layer thickness enabled the final form
dimension to be based on the objective fitness function. A co-simulation using CST and MATLAB was conducted, after optimizing the initial parameters.

Experimental results indicated that the final optimal metamaterial possessed broadband capabilities, high-absorption, low radar cross-scattering, and flexibility. Furthermore, the proposed metamaterial was loaded onto a reference antenna to highlight its radar cross-section reduction capability for passive-equipment EM invisibility. The novel encoding approach facilitated the combination of a genetic algorithm and numerical analysis software to create complex and multifunctional metamaterials with arbitrary characteristics and improve metamaterial applications in microwave devices.

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