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**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 difficultly whileits geometrical architecture is composed of hybrid compositions. However, the genic algorithm as a calculation analogue search algorithm seeking for optimal solution can be applied to artificial metamaterials architecture construction. Herein, a novel encoding strategy of metamaterial architecture construction utilizing multi-parameter seeking optimization was proposed. Binary encoding and decoding of the geometrical layer-thickness enables form final dimension based the objective fitness function. The algorithm iteration optimizes initial geometrical dielectric-layer thicknesses. Then, combining the optimizing initial parameter with composite multi-loops metal spatial distribution built final metamaterials in numerical analysis software. Based on this co-simulation disposition, the proposed metamaterial presents broadband features of 2.5GHz at the physical high-absorption to spatial wave over 80%. The proposed metamaterial presents low radar cross-sections, wide polarization insensitivity, and dynamical flexibility simultaneously. Moreover, a disposition of the proposed metamaterial loaded on a referenced antenna exhibits a well real applicated capability in radar cross-sections reduction for the physical passive equipment invisibility. Numerical simulation and experiment results in MMs properties of the absorption and flexibility show good agreements, suggesting the advantage of genic algorithm optimizations in co-simulation for metamaterials architecture construction which shows a good potential application in spatial complicated geometry forming.

**INDEX TERMS** Genic algorithm, metamaterials, broadband, high-absorption, radar cross scatteringreduction.

1. **INTRODUCTION**

As a kind of artificial materials engineered to have many

uncommon properties, MMs have always been a pervasive research topic of interest in optics [1-3], electronics [4-6], machinery [7-9], even extended to acoustics [10]. Developments of these discipline studies concentrate on more special characteristics or functionality, like [11-13], surface or spatial wave control [14-16], enhancing bandwidth [17~19], radar scattering distribution reduction [20-23], electromagnetic (EM) shielding [24]. Anomalously MMs characteristics always attribute to deliberate architectures out to randomly materials collocation and spatial architecture construction. However, investigating approaches of spatial architecture constructions usually lack

sufficient focus on a simple, sequential, fast, low-cost strategy. Recently, an encoding method for MMs design provides a promising avenue to engineer structure as desired [25-26]. Depending on encoding the surface lattice with binary sequential code [26-27] or redefine special structure with targeting refection phase [28], MMs with excellent properties and multi-functionality are directly reorganization and established. Evolving from analog MMs with periodic particles arrangements, the encoding MMs aim to realize many sound functionalities by restructuring objective function which provides final optimizing goals to the design. Also, genic algorithm (GA) possesses many properties like tunability, robustness, and maturity [29-30] in multi-objective solution, which has widely been used complex goal

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| VOLUME XX, 2017 | 1 |

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disposition [31, 32] to achieve parameter-encoding. The MMs optimization enables dynamically modulate the reasonable parameter code according to the objective function. Based on optimal code sequences of different parameters or structure, both functional requirements and the architecture of MMs can be guaranteed and modeled finally.

With gradient merits of MMs, the improvement of the bandwidth and absorption peak has always been pursued by scholars in radio frequency or microwave (MW) applications owing to the great enhancement of signal capacity and stability [33, 34]. Currently, a great number of general ways have been focused on both of two challenges, such as stacking composite structure [35, 36], using strong magnetic materials [37, 38], combining facial resistance materials [39], multi times resonances [40, 41] facile design of unit structure

1. to widen working band, and constructing fierce LC resonance [43], increasing the loss of dielectric or metal [44] to enhance electromagnetic (EM) wave absorption. Though these methods are finally in favor of promoting MMs applied features, the optimal results come to be unreliable and the experimental process is just independent, even occurring many fake absorptions due to EM wave polarization transforming [45-50]. Relying on the analog metamaterials and the continuous size design, the aforementioned design process is full of complicated and tedious. Thus, encoding artificial MMs severs as a pronounced sound strategy, which provides a precise architecture construction strategy and alleviates the burden from conventional simulating design complexity and multi-parameters global optimization. By the co-calculation and experiments between the commercial software and the optimizing code sequences, the completion of encoding structure constructions can be obtained to meet the complicated goals.

In this paper, a novel encoding strategy utilizing GA in the MMs for forming broadband and high-absorption is proposed. Using GA iteration optimizes initial geometrical layer thicknesses and building the co-simulation between CST and MATLAB software by connecting with parameters code severs as the foundation of the MMs structure. Binary encoding and decoding of the geometrical layer-thickness enables form final dimension based the objective fitness function. After periodically paralleling multi-loops surface profile engineered in CST, the architecture construction is conducted by initial layer thickness and arrangements in spatial metal. The final presented MMs shows excellent properties like broadband, polarization-independent, low radar cross scattering (RCS) level, and wide flexibility.

**II. PRINCIPLE AND METHODS**

1. ***COMPOSITE METAMATERIAL CHARACTERIZATION***

The relationship between MMs functionalities and

architecture parameters is of a precondition to tailor continuous code by GA optimization. As for multi-layer metamaterials, the correlations between layer-thicknesses

and bandwidths and absorptions should be considered first, and the composite substrate thickness determines devices flexibility. According to transmission lines theory, reflection coefficients of MMs can be represented as the formula (1) when the incident wave vertically propagates to the structure surface. The dielectric loss due to the different transmitting rate of EM wave within the different materials is the key to attenuate incident energy for multi-layer metamaterials. The thickness and impedance variety of different substrate are mainly of an impact to control the final absorbent energy. The correlation between the equivalent impedance (*Zn*) and the thickness (*tn*) of the nth layer materials can be described as the formula (2):

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  |  |  | = | | − 0 | | | | |  |  | (1) |  |
|  |  |  |  | + 0 | | |  |
|  |  |  |  |  |  |  |  |  |  |
|  | Z = | | | −1+ tanh⁡( ) | | | | | |  | (2) |  |
|  |  | |  |  | |  |  |
|  |  | | | +  −1tanh⁡( ) | | | | | | |  |  |
|  |  |  |  |  |  |
|  |  |  |  |  | |  |  |  |  | |  |  |
|  |  |  |  |  | | 2 |  |  |  | | (3) |  |
|  | = √ |  | = | |  | √ | | |  |
|  | |  | |  |
|  |  |  |  |  |  |  |  |  |

Where *Z0* is the free spatial impedance 377 , *c* is the transmitting rate of EM wave in vacuum, *f* is the center frequency in working band, *rn* and *rn* is the complex permittivity and permeability of the nth layered material, respectively. The absorption level of MMs can be represented as A( ) =1-R( )-T( ), where R( ) and T( ) are reflectivity and transmittance of EM wave, respectively. T( ) is close to zero when the back of MMs is almost foiled full metal, so the absorption just relates with reflection coefficients.

To access the optimal absorbent bandwidth and rate, the layer-thickness as initial variables should be coded first. Here, the substrate thickness value is of representation with *S*-bit binary coding and the maximum thickness (*tmax*)of eachlayer is only 1 mm. The encoding and decoding process of multi-layer MMs thicknesses shows as Fig.1. (a) and the maximum layer thickness with the relationship of corresponding parameter value precision following:

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| 2 −1 < |  | < 2 | (4) |  |
|  |  |
|  |  | |  |  |

Where *t* is the thickness precision in designing process, defined as 0.001, so the single parameter value can be depicted as a 10-bits code.

***B. OBJECTIVE FUNCTION DEFINITION AND GA ENCODING PROCESS***

Initial optimizations in bandwidths and absorptions of MMs sever as a multi-objective optimization problem. To obtain a higher absorption and wider working bandwidth, the return loss should be always lower than -10dB if the absorption rate is higher than 90%. The objective function should link the absorptivity (A=1-RC, where the backplate is

2 VOLUME XX, 2020

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2

Where the *fi|max* and *fi|min* is the maximal and minimal frequency in the ith working band when A>90%, *fmax* and *fmin* is the upper and lower limit frequency, respectively. Here, the minimum level of the fitness function should be pursued through GA dispositions finally.

Herein, the substrate layer-thickness is regarded as the major calculation factor by GA optimization, which is closing related the material permittivity and permeability effecting the goal function. First, two RF materials of FR4 and Rogers RT5880 are suitable for the electronical loss reduction in many RF devices, like antenna, coupler, absorber, etc. Also, these material with ultra-thin thickness can be bended around a curved surface due to the favorable mechanical properties. In addition, the PDMS as middle sticky layers not only connects with up and bottom substrates but also acts as the flexible dielectric material. Second, once the substrate materials are chosen, a main function about the objective achievement conducts as a round-function to iterate. The boundary condition is depicted as the formula (4).

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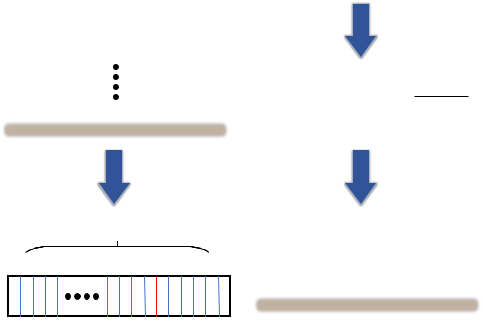


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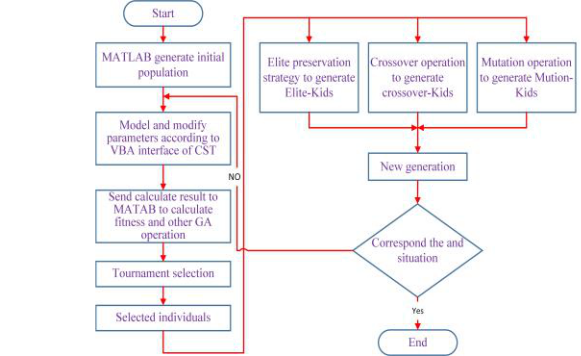


(a)

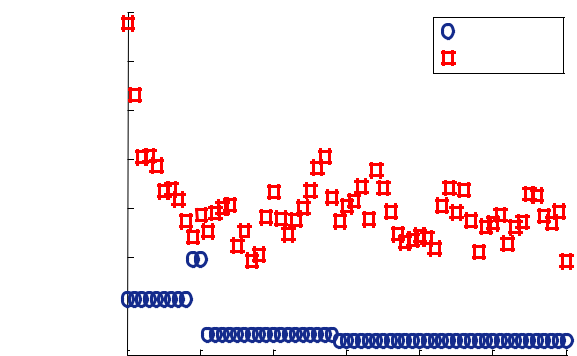
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| *t* | *1* |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| *t* | *2* |  |  | Decoding | | |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  | *u* | |  |  | − *u* |  |
|  |  |  |  |  | *k* |  |  |  |  |  |
|  |  | *t* | *n* | = *u* + |  |  | *bi* 2 | *i* −1 |  |  | 2 | | 1 |  |
|  |  |  | 1 |  |  | 2 | | *k* | −1 |  |
| *t* | *n* |  |  |  |  | *i* =1 |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  | Encoding |  |  | Thickness | | |  |  |  |  |  |  |  |  |
|  |  |  | Forming | | |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |
|  | N\*S Bits |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  | 0111······0010111100····11000 | |  |  |  |  |  |  |  |  |  |  |  |  |
|  | Thickness | Precision |  | Final Thickness Disposition | | | | | | | | | |  |



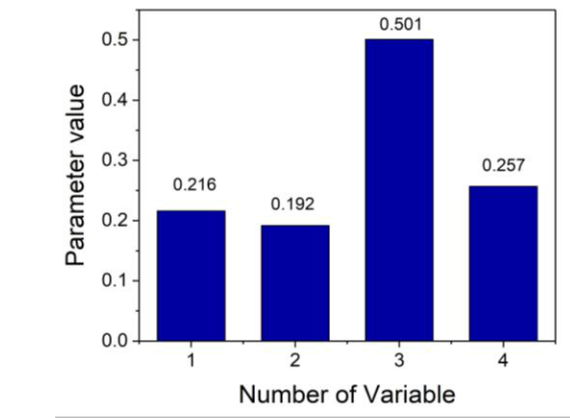
(b)



|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| (c) |  | 0.07 | Best: 0.00294602 Mean: 0.0192528 | | | | |  |  |
|  |  |  |  |  | Best fitness |  |  |
|  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |
|  | value | 0.06 |  |  |  |  | Mean fitness | |  |
|  | 0.05 |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |
|  | Fitness | 0.04 |  |  |  |  |  |  |  |
|  | 0.03 |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |
|  |  | 0.02 |  |  |  |  |  |  |  |
|  |  | 0.01 |  |  |  |  |  |  |  |
|  |  | 0 | 10 | 20 | 30 | 40 | 50 | 60 |  |
|  |  | 0 |  |
|  |  |  |  |  | Generation |  |  |  |  |



(d)



**FIGURE 1. Each generation and different individuals in the GA optimizations process. (a) Diagram of the numerical encoding and decoding process of multi-layer MMs thicknesses; (b) GA operation processing flow diagram for MMs optimization. (c) best and mean fitness value of the individual in every generation; (d) final calculating best individuals.**

pure metal) with the bandwidth together and their calculations must be own identical optimizing weight coefficient. From here, the defined fitness function is the following:

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| = 1 − | ∑ ( | − |min) |  | − |  |
|  |  |
|  | − | |  |  |
|  |  |  |

The main function iterates four times corresponding to four substrate layers. By invoking GA tool in MATLAB, the objective function as the fitness function is calculated to obtain the final optimizing code. Finally, by entering the interface between CST and MATLAB, we establish the

1. interaction between MATLAB and CST. The main program of real coded genetic algorithm is programmed by MATLAB, and the calculation of model is completed by CST.

Fig.1. (b) shows the GA operation processing flow diagram of the MMs optimization. The GA program creates a sequence of initial chromosomes to tune the EM code of each layer, which aims to calculate the final optimizing layer-thickness. The co-simulation has been operated by uniting the CST STUDIO SUITE and MATLAB. The best absorption and the wider bandwidth can be operated by optimizations to the fitness function. In the calculation, the initial population sets 20 in the generation. Two elite individuals in the tournament selection are regarded as the initial individual and other initial individuals are randomly created by rand-functions. The crossover probability set as 0.8, the mutation rate set as 0.01, and the maximum generation number of 60 sets as the stop condition. Modified parameters are obtained after 60 iterative evolutions and the optimal MMs architecture with quart-layer dielectric not only owns bendable properties but also enhance electric loss

VOLUME XX, 2020

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business between different substrates, so all parameters are represented as 40-bits code.

**III.** **EXPERIMENTS AND DISCUSSIONS**

***A.*** ***GA OPTIMIZATION RESULTS***

As shown in Fig.1. (c), the low fitness level stands for a higher EM wave absorption and a wider working bandwidth. Fig.1. (d) shows final optimizing dielectric-layer thicknesses. Initial parameters of the layer-thickness can be characterized when final calculating best individuals are formed. Based on the initial thickness value, the clear MMs formation combining optimizing four layers with special metal structure distributions is further conducted by full-wave analyses in CST and detailed structure configurations proceed in part

**III(B).**

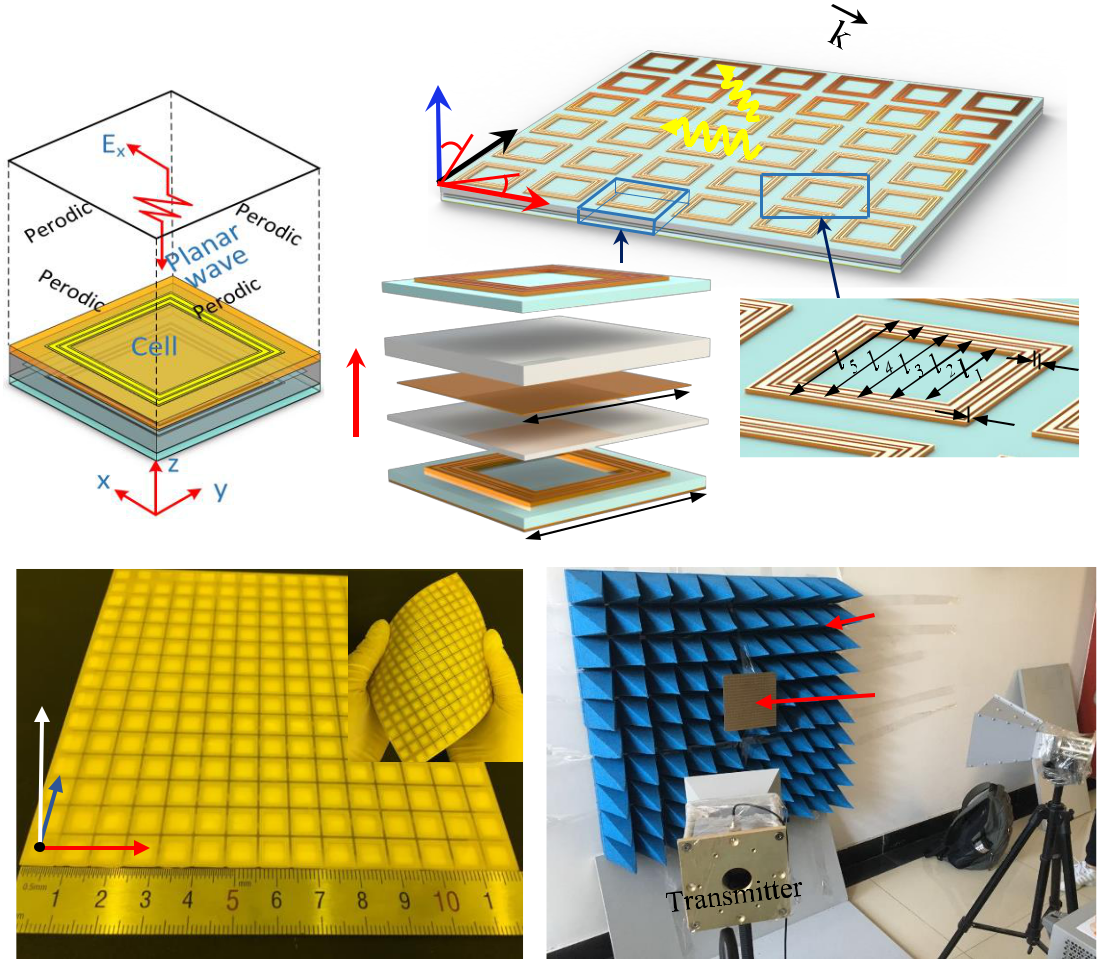
1. ***STRUCTURE CONFIGURATIONS AND PHYSICAL***

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

**Table. 1 Detail architecture spacing dimensions of MMs cell as shown in Fig.2**

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Parameter | *a* | *l1* | *l2* | *l3* |  |  | *l4* | *l5* | | *w1* | *w2* | *dp* | | | | | | | | |  |
| Value(mm) | 8 | 5.02 | 5.44 | 5.61 | 6.03 | | | 6.2 | | 0.15 | 0.4 | 7.37 | | | |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| (a) |  |  |  | (b) |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  |  |  | z | *θ* | y | | |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  |  |  | *O* |  |  |  | *φ* |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  |  |  |  | x | | |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  |  |  | (c) |  |  |  |  |  |  |  |  |  |  |  |  | (d) | | | | |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  |  |  | 4 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | *w2* | | | |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  | *dp* | |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  | *w* | | | | | |  |
|  |  |  | 1 |  |  |  |  |  |  |  |  | *1* | | | |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| (e) |  |  | (f) |  |  |  | (g) | *a* | |  | Absorbing | | | | | | | | | |  |
|  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  | Materials | | | | | | | | | |  |
| z |  |  |  |  |  |  |  |  |  |  | Sample | | | | | | | | | |  |
| y |  |  |  |  |  |  |  |  |  |  |  | Receiver | | | | | | | | |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |



x

**FIGURE 2. Diagram of the designed MM model, fabricated sample and measured system. (a)cell boundary settings in full wave analyses; (b) periodically planar MM structure; (c)spatially detailed cell geometry in a vertical expanded view; (d) special dimension of the metal loops of the partial MM; (e) final fabricate MM using MEMS technology in 10 thousand class preventing dust room; (f) bendable MM; (g) free space test platform for MMs absorption measurement.**

|  |  |
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| VOLUME XX, 2020 | 3 |

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In terms of aforementioned developing layer-thickness parameters, one independent cell comprises back metal layer of the full copper ( = 5.88 + 07⁡S/m) foil, the insulator layer of Rogers 5880 (Ro5880, = 2.2, tan = 0.0009), the five metal resonant square loop (Q-loop) array, the flexible adhesive layer of Polydimethylsiloxane (PDMS, = 2.75, tan = 0.03), the sputtering aluminium (Al, = 3.56 + 07 / ) plate layer, the PDMS layer, the Flame Retardant 4 (FR4, = 4.4, tan = 0.02) layer, and the Q-loops array layer along the structural arrangement from the bottom to the top as shown in Fig.2.(c). The spacing location and the dimension of two Q-loops maintain spatially counterpart in the dielectric plate and the wire width of five Q-loops array is periodical in the sequence of between two sizes (*w1* and *w2*) as shown in Fig.2. (b) and (d). Developed dimensions of each part of the unit cell are illustrated in **TABLE. 1**.

Metal Q-loops arrays on the top and bottom insulator substrate are constructed with the etching process by High-Density Interconnector (HDI) technology owing to the scale of Q-loop arrays on the order of microns. Three times interconnections of the plane between different dielectric are of a realization to multi-layer integration by the cationic bonding technology. The MMs sample is fabricated by Micro-electromechanical Systems (MEMS) technology. The overall prototype consists of 15×15 cells of MMs elements and the area of 12×12cm2 as shown in Fig.2. (e) and (f).

The fabricated sample reveals excellently bendability in a wide-angle range.

Free space test method, as shown in Fig.2. (g), is applied to achieve the absorbing features by transmitting a standard transverse electric (TE) or transverse magnetic (TM) beam from the incident horn antenna to the AMs sample vertically. The TE and TM mode is excited when the short edge and the long edge of the transmitting horn antenna are vertical to the ground, respectively. By modifying the position of the supporting tripod to adjust the incident angle respectively, different polarization and oblique incident responses of MMs absorptivity are measured. An external network analyzer formulates time-domain spectrums in Fourier transform from the transceiver and transmitter to obtain absorptivity.

**Ⅳ. RESULTS AND ANALYSES**

1. ***TRANSMISSION AND REFLECTION COEFFICIENTS***

After optimizations employing GA methods and structure

construction, the final MM presents many bandwidth and absorptivity advantages. Fig.3 shows numerically energy responses and transmitting spectrum at the working band range of 5.5~12.5GHz. It is obviously depicted that power accepted by the entire geometry is more than 80% at the band of 7.81~10.31GHz as shown in Fig.3. (a) and the power outgoing through two ports is of correspondence with absorbing energy in the rated power of 5W. Energy absorbed from both loss from multi dielectrics and metal structure is almost identical in the lower band, but this is only developed

from the loss in substrates in the higher band. Through the presentation of reflection coefficient characterizations as shown in Fig.3. (b), the trends primarily keep pace with the absorbing energy transformation. The anisotropic of different materials in high frequency leads to the tight deviation. Moreover, RCs in the cross-polarization (cro-pol) direction nearly accesses to zero far below that in the co-polarization (co-pol), which indicates the EM wave absorbed focusing on the absorption by proposed MMs instead to the wave transformation. Also, the transformed intensity (720°) of the cross-polarized reflective phase is far more than the co-pol level (-88.7°~64.0°) and strongest changes of the phase difference in co-pol mostly excite in the endpoint of the working band as shown in Fig.3. (c). This longer delay of the reflected phase in the cro-pol direction exhibits little EM wave returned to the output port, which further verifies the definite absorption by MMs instead of the polarized transformation. The absorptivity of the proposed MMs is shown in Fig.3. (d) when TE and TM wave is normally propagating to the proposed MM. The absorption in TE and TM incident wave almost maintain uniform and the only little discrepancy is presented at 8.8GHz as the electric dipole absorption is stronger than the magnetic absorption to the multi Q-loops structure feature. The broadband of valid absorption over 80% nearly achieves 2.4GHz (7.8~10.2GHz) and broadband responses attribute to the MMs possessing well continuity of effective resonances to different Q-loops and strong dielectric losses to structural composite layer. Furthermore, the broadband feature complies with the ultra-wideband principle [41] which can be formulated as BW = (  ( ≥0.8) − ( ≥0.8))⁄ > 25% (*fc* is the center

frequency of working band.) and the actual BW level of the proposed MMs equals to 26.7%.

***B.*** ***BROADBAND PROPERTY VERIFICATION***

In TE polarization mode, electric property representations which are shown as the E-field distributions in Fig.4 are of a sign to verify the broadband implementation derived from complex resonances. Cell profiles E-field in the strongest electric position are shown in Fig.4. (a)~(c) versus the working frequency of 8GHz, 9GHz, and 10GHz, and three fierce electric configurations present a downtrend from the position of superficial Q-loops, among superficial Q-loops and upper FR4 layer with increasing frequency. According to superficial E-field distribution as shown in Fig.4. (d)~(f), the strong resonant location is gradually deviated from outer to inner loops, which bears out the negative correlation between the electric resonant path with the working frequency. Q-loop bilateral metals with strong electric distribution develop bi-parallel capacitances as the side potential is higher the middle of each cell, which exhibits electric resonances from the equivalent capacitance response. The physical structural arrangement of sequential metal loops and corresponding extended depth of the dielectric resonant locations facilitate the effective formation of the MMs absorbent wideband.

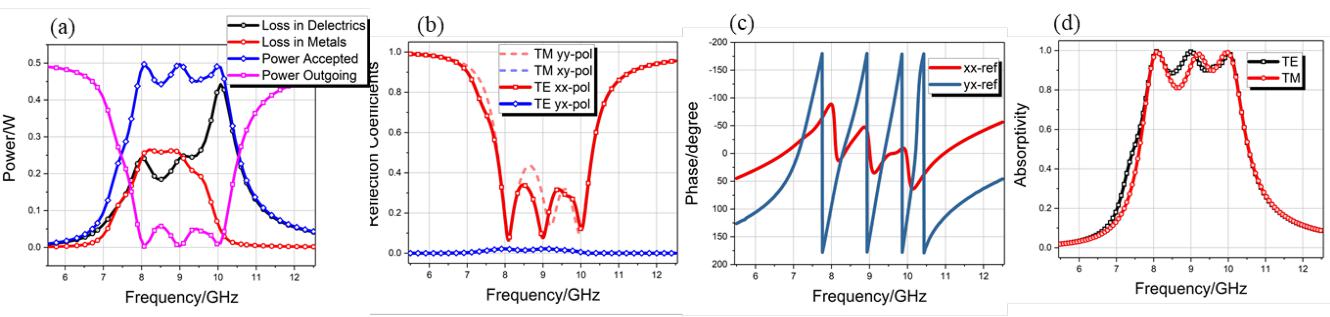
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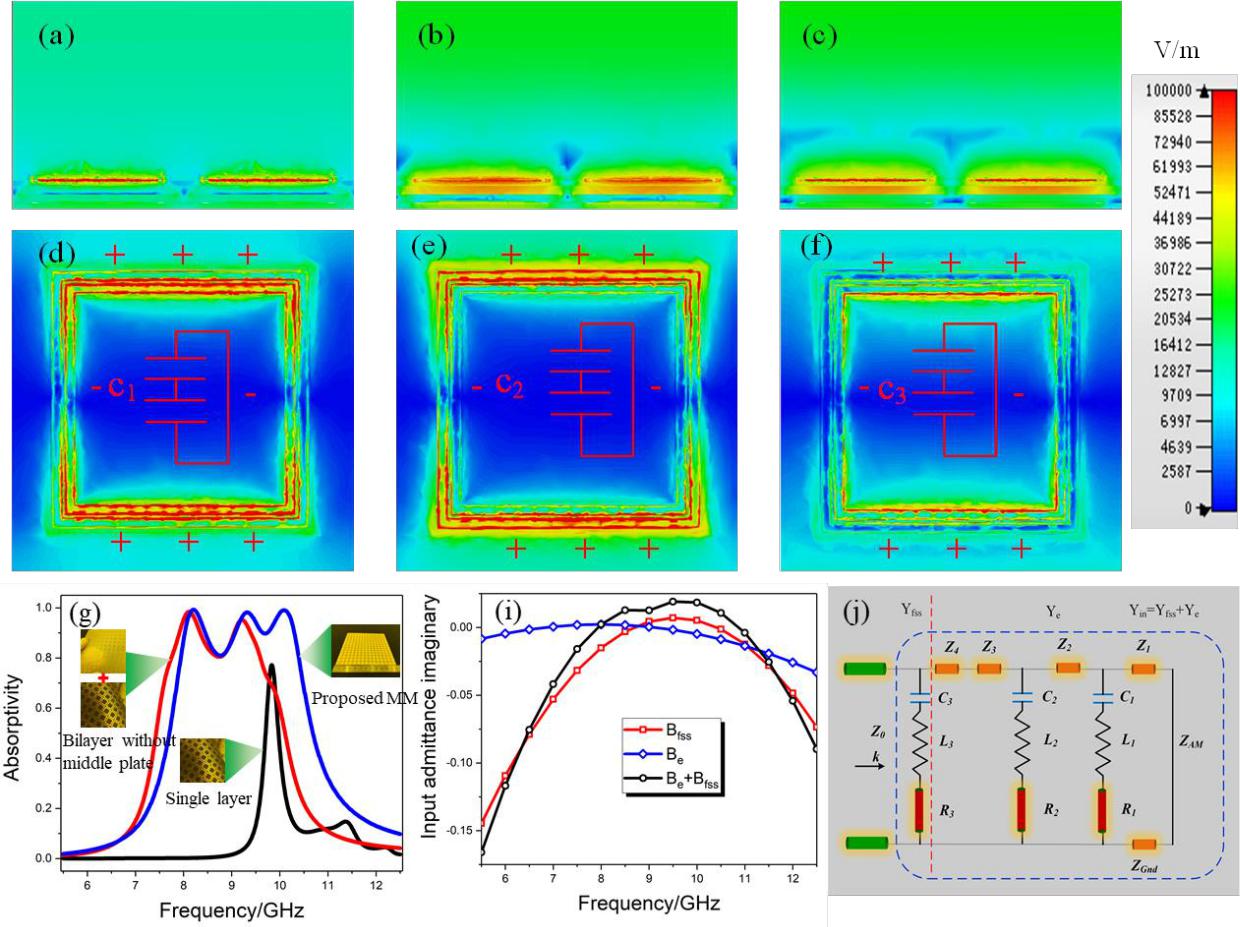
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**FIGURE 3. Numerically energy responses and transmitting spectrum of proposed MMs. (a) accepted and outgoing power responses in full wave analyses from two ports and the loss of applied material; (b) co-pol and cro-pol reflection coefficients of the MM in the incidence by TE and TM wave vertically; (c) co-pol and cro-pol reflection phase in the incident TE wave; (d) absorption of the MM in two mode.**



**FIGURE 4. Sectional and top electric field (E-field) distribution in the strongest resonant position for each cell at different working frequencies. (a) and**

1. **8 GHz; (b) and (e) 9GHz; (c) and (f) 10GHz, respectively. Absorbent response comparison of different layer structure and equivalent LC circuit of MMs.**
2. **comparison of the absorption rate between different structure composed of single layer material, bilayer dielectric and final MM; (i)electric conductance of top Q-loops and the bottom composite structure; (j)equivalent active circuits of the MMs with multi-layer substrates.**

To verify the broadband feature based on the GA optimization, different assembles of the proposed MM with single layer or bilayer, and final MMs are tested in sequence as shown in Fig.4. (g). The single-layer material only shows one absorbent peak at high frequency while the bilayer MM without etching the middle metal layer shows wideband absorption across part lower frequency. By contrast, the bandwidth improvement indicates the broadband feature attributing to the interstratified dielectric loss and paralleling

equivalent capacitance attenuations which are led by the potential difference between the middle metal and 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 dielectric layer contains a certain impedance. The equivalent input admittance of the circuit can

be presented as = + . *Yfss* and *Ye* are the equivalent admittance of the superficial metal and the bottom multi-layer

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architecture, respectively. And equivalent admittance can be represented as = + , *G* is electric conductance. When the electric susceptance (*Be*) of equivalent LC circuit is close to zero the proposed structure can excite an effective resonance with just impedance characterization access to perfect EM wave absorption. Using the equivalent circuit inversion method, the electric susceptance of the superficial metal and the bottom composite architecture are calculated as shown in Fig.4. (i). The sum of two electrical susceptance mainly keeps a level of zero among the high absorption wideband, which keeps numerically and theoretically in accordance with the MMs absorbent performance of in the wideband range.

***C. POLARIZATION CORRELATIONS AND RCS DISTRIBUTION***

MMs Polarization is of key indicator to evaluate the tolerance that decides MMs EM wave features-selectivity.

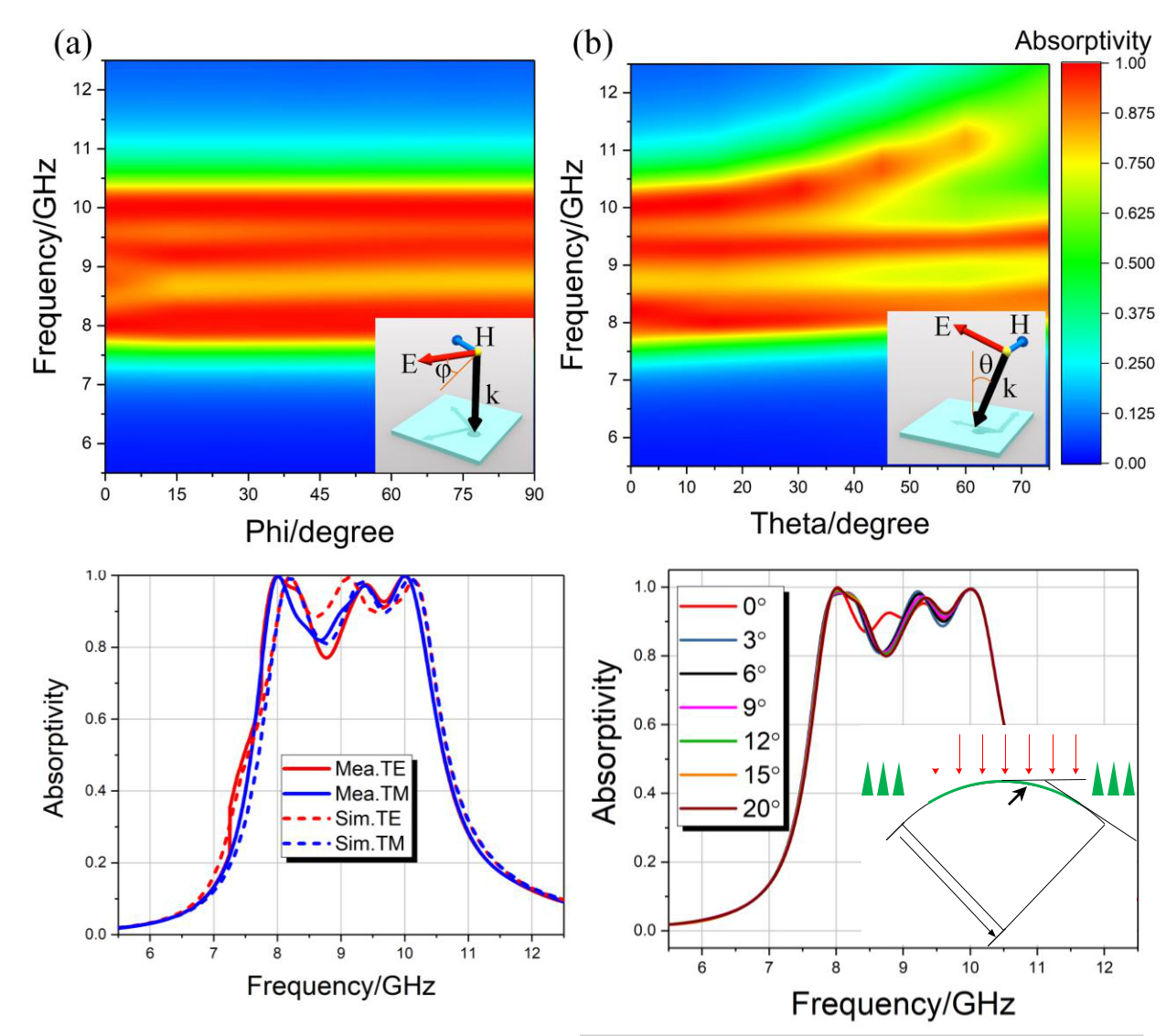


Fig.5. (a) shows the absorptivity of the proposed MM under the normalized polarized TE wave with different polarization angles. The obvious polarization-independent angle exhibits the favorable absorbance in wideband range when the MM absorption over 80% keeps stable and high level with the changes of the polarized angle at the band range of 7.65~10.38GHz. The little EM wave in TE mode is absorbed with the increase of the oblique incident angle, however, the absorptivity over 60% is still achieved at 7.5~10.5GHz when θ<50°, as shown in Fig.5. (b). The fractional bandwidth with the absorption over 80% of the proposed MM absorber is 39%. As for microwave devices, the relative bandwidth over 25% can be defined as the ultra-bandwidth, so this proposed

1. absorber is the ultra-bandwidth MMs. Additionally, the absorbent responses in both incident modes keep a high level in a wide incident angle range, which validates the polarization insensitivity of the proposed MM adequately.

(c) (d)

TM 



Wedge- AM*α*

tapered  ~~Foam~~

Absorber Cylinder

*r*

**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*.**

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| VOLUME XX, 2020 | 3 |

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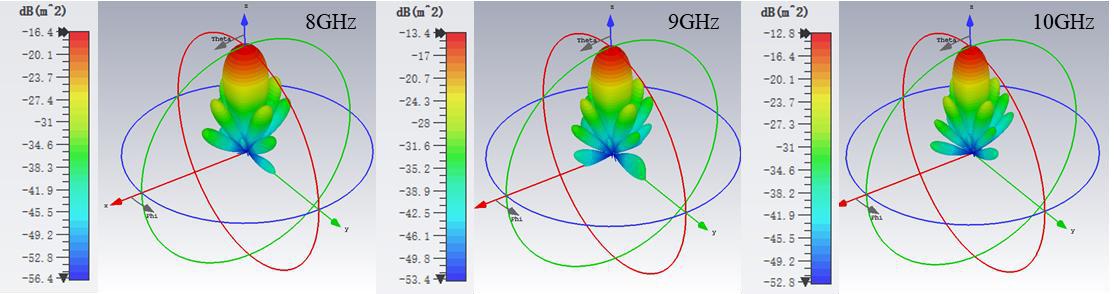


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**Table 2. Comparison of the metamaterial thickness with the GA optimization and superior broadband feature of our MM with the previously reports**

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
|  | ID | Thickness | FBW/GHz | Incident angle | Flexibility | Function |  |
|  | (in wavelength) | tolerance |  |
|  |  |  |  |  |  |
|  | Reference[16] | 0.033 0 | 9.53~10.42 | <45° | No | Absorption |  |
|  | Reference[17] | 0.037 0 | 10.1~10.4 | \_\_ | No | Absorption |  |
|  | Reference[24] | 0.061 0 | 8.56~10.21 | \_\_ | Yes | EM |  |
|  | shielding |  |
|  |  |  |  |  |  |  |
|  | Reference[18] | 0.018 0 | 1.8~2.3/2.4~2.6 | \_\_ | Yes | Frequency- |  |
|  | selective |  |
|  |  |  |  |  |  |  |
|  | Reference[36] | 0.018 0 | 4.75~5.2 | >45° | No | Absorption |  |
|  | Reference[42] | 0.084 0 | 3.7~8.5 | <20° | No | Absorption |  |
|  | Our work | 0.035 0 | 7.56~10.62 | >45° | Yes | Absorption |  |



**FIGURE 6. RCS radiative distribution of the proposed MM with the cell arrangement of 15×15 at three working frequencies of 8, 9, 10GHz**

Additionally, the RCS of general architecture stands for the special invisibility level in fierce EM environments. Fig.6 shows the MMs RCS radiative distribution with the cell component of 15×15 at three working frequencies of 8, 9, 10GHz, which obviously exhibits the strong RCS level along with the AMs’ normal direction. As the unabsorbed EM wave along the normal direction is fully reflected by the MM, the other direction couples with more lower scattering wave. Moreover, each strongest level, -16.4, -13.4, -12.8dB in three working frequencies, is lower than the rating value of -10dB in EM interference discipline. The excellent RCS level illustrates the proposed MMs with good invisibility which can be applied in radar applications widely. The fractional bandwidth with the absorption over 80% of the proposed MM absorber is 39%. As for microwave devices, the relative bandwidth over 25% can be defined as ultra-bandwidth devices, so this proposed MM absorber is the ultra-bandwidth MMs. Note that the most significant merit of our MM is the rational combination of the metamaterial construction design with the GA optimization and superior broadband feature, which is higher than other peers’ works reports with similar periodical metamaterial as shown in Table 2. In the comparison, our work about the optimizing

1. possesses the wider bandwidth and optimal incident angle tolerance.
2. ***EXPERIMENTAL VERIFICATION AND ARRAY ANTENNA RCS REDUCTION***

To verify the broadband absorption validity, MMs physical absorptivity in real free space experiments are measured. In TE and TM mode, Fig.5. (c) shows the experimental absorptivity which makes a greatly agree with simulation data. between practical and numerical results attributes to the errors of the MEMS manufacturing precision and the test process. Additionally, to verify the polarization sensitivity and flexibility of the proposed MM, warping the thin MM around a foam cylinder with the radius of *r* tests the bent absorptivity as shown in Fig.5. (d). When the radius of the cylinder is decreased the absorbent peak develops slight right-shift of 23 MHz.

With high absorption and low RCS, the proposed MM shows great potential capabilities in passive equipment invisibility. Here, a 6×5 planar array antenna as shown in Fig.7. (a) is utilized to the RCS reduction of the proposed

1. in mono station radar detection. As shown in Fig.7. (b), the antenna array parallels with the MM and the spacing between the reference array and the fabricated absorbent MM is three working wavelengths ( 0 is the corresponding working frequency of 9GHz), where the ground plane of the MM is not removed when the test is conducting. Fig.7. (c) shows both the numerical and experimental return loss (S11) below -10dB at the resonant frequency of 9GHz exhibits good impedance matching performance. As for microstrip patch antenna, the coaxial probe as the power input was connected with the high frequency signal. The quality

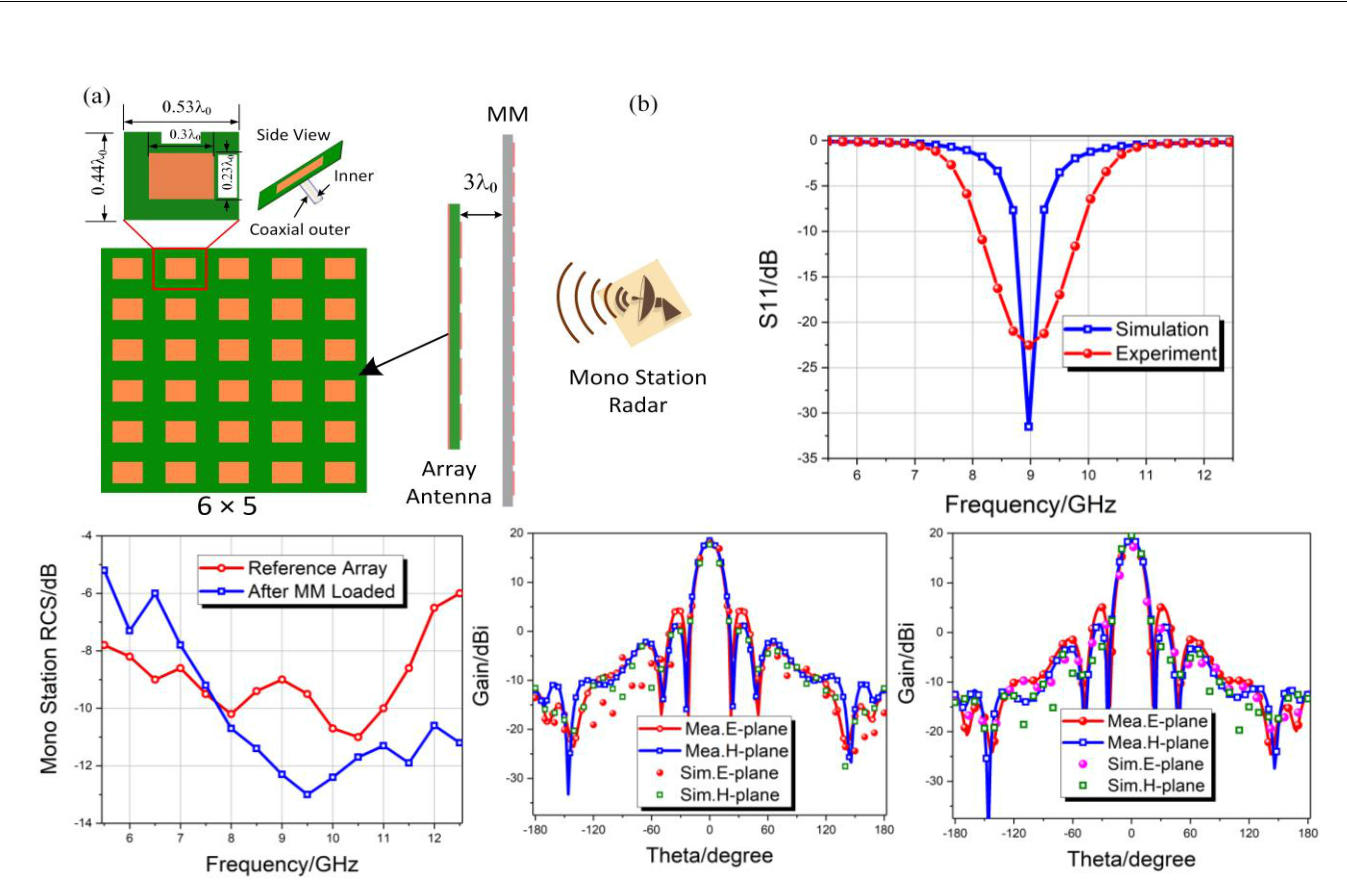
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(c)

(d) (e) (f)

**FIGURE 7. Application of the proposed MM to the array antenna. (a)diagram of the reference planar array antenna and its elements detail profile; (b) paralleling disposition of the MM loaded on the array. (c)numerical and experimental return loss of the array antenna cell; (d) RCS distributions of the reference antenna and after MM loaded on the top of antenna; (e) and (f) measured and numerical radiation pattern of the reference array antenna loading with the proposed MM in E-plane and H-plane, at 8.5GHz and 9GHz respectively.**

transmission of RF signal will be reduced when the fabricated precision of coaxial probe with little deviation leads to relatively larger error at high frequency, so the experimental resonant depth is lower relative to the simulation data. Also, the impedance bandwidth of the coaxial connector at high frequency is wider corresponding to at low frequency due to the easily establishment of impedance match between the coaxial probe with the patch antenna, so the experimental bandwidth is wider than the simulated data. The RCS distribution along normal direction always keeps the highest level since the vertical section of passive equipment is largest in relative with a transmitting radar. Through paralleling disposition of the MM, the RCS distribution along the normal direction of the array antenna is tested as shown in Fig.7. (d). After MM loaded on the reference antenna, the RCS distribution is obviously reduced at the MM high absorption band, which illustrates a certain positive correlation of MMs between RCS reduction and EM wave absorption. The RCS high level in low-frequency band attributes to the entire structure dimension increase and the unmatching resonant size with the radar wave. Finally, the radiation pattern of the reference array antenna loaded with the proposed MM is tested at 8.5 and 9GHz in the microwave chamber and the simulation pattern is described as shown in Fig.7. (e) and (f), respectively. It can be found that the array antenna still owns a higher realized gain and lower side lobe level after load on the proposed MM. The tested radiation

pattern keeps greatly in accordance with the simulation data. Additionally, the radiation pattern almost keeps identical level in the realized gain and the transforming trend at different frequency points. Through RCS distribution applied application for array antenna, the proposed MM with the high absorption contributes to passive equipment RCS reduction and shows the potential value in EM interference invisibility.

**CONCLUSION**

This paper developed a novel encoding strategy of metamaterial architecture construction by means of genic algorithm multi-parameter seeking optimization. Multi-objective function operations built geometrical layer-thickness parameters in relationship with both the broadband and reflection coefficients. Digital binary encoding and decoding of the geometrical layer-thickness enables form final dimension based the objective fitness function. Applying optimizing initial parameters, the co-simulation between numerical analysis software and MATLAB was conducted. Experimental results indicated that the final optimal metamaterial is of possessions with broadband, high-absorption, low radar cross scatting, and flexibility. Furthermore, one application of the proposed metamaterials loaded on a referenced antenna highlights the radar cross-section reduction capability for passive equipment EM

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| VOLUME XX, 2020 | 3 |

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invisibility. The novel encoding approach is able to facilitate the combination operation between the genic algorithm and numerical analysis software for complex and multifunctional metamaterials to accomplish arbitrarily characteristics and enrich the applications of metamaterials in millimeter wave devices.

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*(Hongcheng Xu and Jianli Cui contributed equally to this work.)*

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