Topology optimization design of a lightweight ultra-broadband wide-angle resistance frequency selective surface absorber

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Abstract
In this paper, the topology design of a lightweight ultra-broadband polarization-independent frequency selective surface absorber is proposed. The absorption over a wide frequency range of 6.68–26.08 GHz with reflection below ~10 dB can be achieved by optimizing the topology and dimensions of the resistive frequency selective surface by virtue of genetic algorithm. This ultra-broadband absorption can be kept when the incident angle is less than 55 degrees and is independent of the incident wave polarization. The experimental results agree well with the numerical simulations. The density of our ultra-broadband absorber is only 0.35 g cm⁻³ and thus may find potential applications in microwave engineering, such as electromagnetic interference and stealth technology.

Keywords: frequency selective surface (FSS), topology optimization, absorber, ultra-broadband

(Some figures may appear in colour only in the online journal)
the fields of structural mechanics, and lately has been applied to tailoring new materials or structures in various fields of engineering such as fluid dynamics, micro-electro-mechanical systems, photonics, and multi-physics effects [15–20]. When used in designing FSSs, those methods provide superior structure optimization strategies by simultaneously considering size, configuration and shape of the unit cell, with a certain objective function under geometrical and/or physical constraints. Generally, most designs of FSSs are multi-objective optimization problems, which require a more robust topology optimization method with multi-objective evolutionary algorithms. So, some of the original numerical methods like the level set method [21] and solid isotropic material model [22] seem to be inadequate, and thus some improved methods like the population-based incremental learning algorithm, non-dominated sorting genetic algorithm (GA) and particle swarm optimization method [23, 24] were applied. Among the algorithms, GA has gained more preference in many applications [25–27] especially in the optimization of FSSs due to its maturity, robustness and tunability.

In this paper, we develop the topology optimization method base on GA and apply it to the design of FSSAs. Using this method, a binary coding matrix can be established by analyzing the symmetry of FSSA structures, which can improve the convergence speed of optimization and the FASSA stability of the incident angle. For instance, a lightweight ultrabroadband polarization-independent frequency selective surface absorber (FSSA) is proposed, according to topology design, where absorption is more than 90% ranging from 6.68 to 26.08 GHz.

2. The method of designing FSSA by topology optimization combined with GA

2.1. Encoding approach of topology optimization

According to the schema analysis of GA, the evolutionary structural optimization is just an evolution process under a certain optimization strategy, with which the schema is related to the defining length of the chromosome and thus decides the code number. Actually, the code optimization strategy can be inspired by analyzing the symmetry of FSSA structures, which in many cases is decided by the physical constraints and application goals. Considering the fact that FSSAs with stable performance under various incidence angles and different polarizations are widely desired in many fields, here we focus on the structures of center-symmetry. As shown in figure 1, the optimization area is divided into $M \times N$ (in this paper $5 \times 10$) small squares marked by 1 or 0. The code 1 means that the small square is filled up with the resistive patch, and the code 0 means being filled up with air.

2.2. Configuration and parameters

The schematic of the suggested FSSA is shown in figure 2, where consists of a periodic array of the unit cell. The unit cell configuration parameters of the FSSA are also shown in figure 2. A FSSA unit cell is composed of three layers: The resistive patches with their topology structure on the top layer; the polyurethane foam substrate located in the middle layer; the bottom layer is a metal slab and the metal is copper with the electric conductivity assumed to be $\sigma = 5 \times 10^7 \text{s m}^{-1}$. The FSSA unit cell dimension: $p$ is the length of unit cell; $w$ is the gap width between two unit cells; $h$ is the thickness of
foam substrate, \( ohm \) is the sheet resistance and the topology resistive patches dimension are determined by \( a = (p - w)/20 \), respectively. The configuration parameters are coded in binary code, which can be decoded as follows:

\[
\begin{align*}
p &= (16 \times p1 + 8 \times p2 + 4 \times p3 + 2 \times p4 + 1 \times p5) \times 0.25 + 4 \\
w &= (8 \times w1 + 4 \times w3 + 2 \times w4 + 1 \times w5) \times 0.1 \\
ohm &= (16 \times ohm1 + 8 \times ohm2 + 4 \times ohm3 + 2 \times ohm4 + 1 \times ohm5) \\
h &= (8 \times h1 + 4 \times h3 + 2 \times h4 + 1 \times h5) \times 0.2 + 1
\end{align*}
\]

where \( p1 \sim p5, w1 \sim w4, ohm1 \sim ohm5, \) and \( h1 \sim h4 \) are binary codes (a total of eighteen).

2.3. Realization of the GA and the combined simulation optimization

A numerical simulation is performed for the FSSA in figure 1 with a commercial program (CST Microwave Studio TM 2011) and optimized by GA based on Matlab. Periodic boundary conditions are used in the X and Y directions, and a plane wave is incident downward on the FSSA with the excitation source \( \text{Zmax} \). Transmission \( T(\omega) \) and reflection \( R(\omega) \) are obtained from the frequency-dependent \( S \)-parameter \( S11(\omega) \) and \( S21(\omega) \), that is, \( T(\omega) = |S21(\omega)|^2 \) and \( R(\omega) = |S11(\omega)|^2 \). The absorption is calculated as \( A(\omega) = 1 - T(\omega) - R(\omega) \). Since the ground is metal, \( S21(\omega) \) is nearly zero in the entire investigated frequency range.

The absorber optimization design is a multi-objective optimization problem, so the working band, the bandwidth and the absorption should be considered simultaneously in calculating the fitness function. In the simulation frequency range \( [F_{\text{min}}, F_{\text{max}}] \) (where \( F_{\text{max}} \) and \( F_{\text{min}} \) are the upper and lower limit frequencies), the optimization goal is to make the absorption bandwidth as wide as possible and meanwhile the absorption meets a certain minimum requirement. Considering these two optimization goals, we set the absorption to not less than 90%, and the fitness function is

\[
f = 1 - \frac{\sum_{i=1}^{n} \Delta F_i}{F_{\text{max}} - F_{\text{min}}}
\]

where \( \Delta F_i \) is the frequency interval distance in which the absorption is not less than 90% continually. Equation (2) indicates that the wider the bandwidth, the smaller fitness value we will get, supposing the absorption is more than 90%.

Combining with CST and Matlab, the joint simulation system has been established. Figure 3 illustrates the flow chart of the process of topology optimization combined with GA. In the calculations, the fitness function is created according to the goal of the own design object, in which considered is the maximal absorption bandwidth and minimal thickness. In GA, 100 populations are employed in a generation and the selection scheme is tournament selection with two best individuals reproduced, realizing the uniform genetic and mutation process. The crossover probability is set as 0.8, the mutation rate set as 0.01 [28], and the stop condition is related to the fitness goals or is set as truncation limited by the maximum generation number of 30.

3. Simulation and experiment

3.1. Optimization result of simulation

The optimization results were obtained by combined simulation after 30 iterative evolutions and the results are shown clearly in figure 4, where \((a)\) shows that the smaller the fitness value the wider the bandwidth of absorption over 90%.
The current best individual is the best parameter binary code of each generation during the algorithm evolution, shown as figure 4(b), and the 68 binary codes include 50 topology codes and 18 parameter codes.

According to the optimization simulation result, the absorption over a wide frequency range of 6.68–26.08 GHz with reflection below $-10 \, \text{dB}$ can be achieved by optimizing the topology and dimensions of the resistive frequency selective surface by virtue of GA.

3.2. Parameter analysis

In figure 5, the absorption influences of sheet resistance are shown considering both optimized and unoptimized cases as a comparison, indicating that the parameters of sheet resistance have great influence on the absorbing properties.

According to the optimization simulation result, the absorption over a wide frequency range of 6.68–26.08 GHz with reflection below $-10 \, \text{dB}$ can be achieved by optimizing the topology and dimensions of the resistive frequency selective surface by virtue of GA.

According to [29], the equivalent circuit method analysis can explain the influences of resistance and the absorption and it also can explain the working mechanism of the absorbers. As a conclusion of the reference, the lower and upper limit of the surface resistance can be found. When the surface resistance is less than the lower limit, there are two absorption nulls with undesired broadband absorption (with reflection above $-10 \, \text{dB}$ at some frequency); since the surface resistance becomes larger and larger (no less than the lower limit and no more than the upper limit), the two absorption nulls gradually move together and then the maximum bandwidth can be achieved with proper resistance; as the surface resistance growth is more than the upper limit, there is only one absorption null. From figure 5, the simulation result has great accordance with the analysis above. It can be found that there are two absorption nulls with a smaller surface resistance such as $30 \, \Omega \, \text{sq}^{-1}$ and $40 \, \Omega \, \text{sq}^{-1}$; thus, a wideband metamaterial absorber can be obtained. However, since the resistance becomes larger and larger (upper limit), only a narrow broadened (even single) absorption null can be observed. It is noted that the central frequency, 15.5 GHz in our case, is approximately equal to the $\lambda/4$ resonant frequency of the dielectric substrate, which is independent of the surface resistance.

In figure 6, the polarization and angular dependence of the FSSA is discussed. Due to the symmetry of the designed FSSA, the absorption is independent of polarization. The absorption effect is robust for non-normal incidence, of which TE and TM polarization are taken as an example. For instance, the absorption of TE polarization is nearly independent of the incident angle below 40 degrees, and as the incident angle increases further, the absorption becomes weaker. Nevertheless, the absorption still remains above 80% even when the incident angle reaches 55 degrees.

To better understand the physics of the suggested ultra-broadband FSSA, the surface power loss density at 8.0 GHz, 15.5 GHz and 26.0 GHz are depicted in figures 7(a)–(c) respectively. It is evident that, according to the power loss density distributions, at a certain frequency, the electromagnetic field is resonantly localized and absorbed at some different parts of the resistive patches, which means different resonant modes.

3.3. Experiment and result

FSSA is made from carbon films prepared by the spraying technique, and the surface resistance is controlled by the thickness and measured by the 4-pont probe. The fabricated
FSS was then mounted above a grounded low-loss foam board with a relative permittivity of 1.1, as shown in figure 8. The surface resistance of carbon films is equal to $40 \Omega \text{sq}^{-1}$, and the dimensional parameters are $p = 11.25 \text{ mm}$, $w = 0.6 \text{ mm}$, $h = 3.6 \text{ mm}$, and $a = 0.5325 \text{ mm}$. The size of the fabricated absorber is $300 \text{ mm} \times 300 \text{ mm}$. Measurement was performed by using an Agilent 8720ET network analyzer with horn antennas working at different frequency bands in a microwave anechoic chamber. The measured result is presented in figure 9. One can see that the agreement between the experimental and simulated results is acceptable except for the small differences at some frequencies.
4. Conclusions

We develop the topology optimization method and apply it to the design of FSSAs. Using this method, a binary coding matrix can be established by analyzing the symmetry of FSSA’s structures. To verify the efficiency of the method, the topology design of a lightweight ultra-broadband polarization-independent FSSA having a broadband bandwidth in the frequency range 6.68–26.08 GHz is proposed. The results show that the performances such as the stability of incident angles, the absorption, and polarization independence are all improved compared with un-optimized FSSA. What should be noted is that this method is a special approach to the design of FSSAs having some symmetrical structures, especially centre symmetry. With a properly modified fitness function, this method can be extended to the design of FSSs, the electromagnetic band gap and other metamaterials.

Acknowledgments

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