Frequency-Selective Surface Stopband Designed with a Genetic Algorithm for Gain Enhancement of a Broadband Monopole Antenna

DucDung Nguyen* Chulhun Seo*

Abstract

This paper presents an unusual, high-performance, cost-efficient, wideband frequency-selective surface (FSS) designed with a genetic algorithm (GA) and its effect on the performance of a broadband M-shaped monopole antenna. Each FSS unit cell with the dimensions of \(0.2 \lambda_0 \times 0.2 \lambda_0 \times 0.01 \lambda_0\) acts as a stopband filter for a wide bandwidth of 5.5 GHz (105%, 2.6–8.1 GHz). The FSS properties and advantages to antennas were tested via numerical simulations and measurements, respectively. Using the 6×6 array of the designed FSS unit cell as a reflector, the antenna impedance bandwidth improved from 96.1% (3.1–8.1 GHz) to 98.07% (3.3–8.4 GHz), with a center frequency of 5.2 GHz. In addition, the antenna gain improved at the maximum of 7.8 dBi, which was sustained from 9 dBi to 10.1 dBi for the entire bandwidth.

Key Words: broadband, frequency-selective surface, genetic algorithm, monopole antenna.

I. INTRODUCTION

The improvement of wireless technology has brought forth the need for wireless terminals miniaturization, which has led to the design of high-gain, multiband, or broadband antennas for communication applications. Printed antennas, with their advantages such as light in weight, diversity, low fabrication cost, and have become especially important. However, they have some drawbacks that is, their low-gain, high-profile, and low-impedance bandwidth and their unwanted radiation, which still challenge researchers. Several techniques have been proposed to improve antenna performance, but periodic structures such as a frequency-selective surface (FSS) [1] have attracted much attention.

FSS is one of the fundamental technologies that have been used for many high-performance applications such as, in the military, for manufacturing radars, wireless security, beam splitters [2], absorbers [3], and especially, antenna-based applications [4–5]. FSS exhibits an instantaneous response constructed by the replication of a pre-design unit cell element. It has two main functions: first, as a derivative filter or spatial filter that allows electromagnetic (EM) wave transmission, known as a pass-band filter [6–8]; and second, when the EM wave is reflected, as a stop-band filter [9–12]. In scientific literature, various researchers had used the FSS structure as a reflector or superstrate to improve antenna performance in terms of radiation characteristics (antenna gain, directivity, front-to-back ratio). For instance, in [13], it was shown that an FSS can be designed by using slots...
or patches in the form of strips, loops, and selective combinations, which can function as filtering elements, but the FSS operation was limited to a single band. In [14], a dual-band FSS was embedded in the antenna, and the gain was enhanced in two bands by 46% and 30%, respectively. Likewise, in [15], a dual-band FSS with double rectangular ring elements was proposed to improve the performance of the microstrip slot antenna. At this time, a maximum gain of around 5 dBi had been obtained, which improved the impedance bandwidth by only 2.37% at 2.45 GHz and 2% at 5.8 GHz. Other common applications of FSS were illustrated in [16–21]. Generally speaking, those reports utilized the classical design methods and proposed fundamental structures, which resulted in certain disadvantages such as low gain enhancement, low impedance bandwidth, high profile, and difficult manufacture.

Furthermore, many methods of synthesizing and optimizing novel material structures have been proposed, such as the simplex method and the genetic algorithm (GA). Among these methods, conventional GA (combined with assignment simulation software) is stable and highly efficient. A version of the ant colony optimization (ACO) algorithm had been implemented to automatically design a microstrip patch antenna that operates at 3.5 GHz with a bandwidth of 50–170 MHz [22]. In [23], GA was used to develop a high-absorption, wideband metamaterial absorber. Besides, the design of other structures that use conventional GA has been reported [24–25]. However, the designs in those reports were complicated and required many function evaluations. Recently, a variant of the conventional GA, called real-coded GA (RGA), was used because of its simplicity and its direct operation on the parameters. Therefore, in this paper, an unusual single-layer, wide-bandwidth, high-performance FSS structure designed with a GA and its effect on the antenna radiation pattern characteristics (antenna gain, directivity, and front-to-back ratio) are presented. The proposed FSS, which uses the RGA-based symmetric inserting selection strategy, responds to the design requirements, diminishes the design time, and avoids the regular structure design limits of human intellectuals. After the FSS was implanted, the antenna impedance bandwidth improved from 96.1% to 98.07% with the center frequency of 5.2 GHz. Moreover, the antenna gain showed a maximum enhancement of 7.8 dBi for a peak gain of 10.1 dBi, and the gain was sustained at higher than 9 dBi, unlike as reported studies.

II. FSS UNIT CELL DESIGN

Initially, the FSS unit cell substrate was chosen and implemented on the substrate of FR-4 Epoxy with a dielectric constant of $\varepsilon_r = 4.4$, a loss tangent of $\delta = 0.02$, and a thickness of 0.8 mm, as it is low-cost and easy to manufacture. Then, we set up the properties of the chosen substrate with an assumption dimension of 13 mm, the fundamental requirements, and the design specification targets of the GA program. The GA process was simplified as shown in Fig. 1. In other words, the top surface of the FSS structure unit cell was subdivided into $N \times N$ specific cells. At this time, to improve the insertion selection speed of a cell and the angular stability of the unit cell, the symmetric criterion was chosen. The non-conducting or conducting property of each cell was described using binary encoding. As shown in Fig. 2, in the case of the conducting cell, the corresponding gene was nominated as 1; and in the case of the non-conducting cell, the assigned gene was 0.

The results were satisfactory at $N = 9$ cells (cell size = 0.705 mm) on a quarter of a unit cell. A perfect unit cell was formed when the designed cell was replicated into four symmetrical cells across the center.

The following steps detail this process.

1. Generate a random string of binary numbers.
2. Generate the shape of the FSS reflector from the binary matrix.
3. Create the models of the symmetric condition unit cell with the chosen substrate and solve the models using the High-Frequency Structure Simulator (HFSS) software.
4. Export the S-parameter ($S_{11}, S_{21}$) results of the models to a data file.
5. The fitness function is the link between the physical shape and the optimization produces.

Fig. 1. Flowchart of the genetic algorithm (GA) for the frequency-selective surface (FSS) reflector design.

Fig. 2. Example of a model corresponding to a binary matrix.
The fitness function is given by:

\[ F = \sum S_{21}(i), \text{ with } i \in (2.5 \text{ GHz} - 8.5 \text{ GHz}) \]  \hspace{1cm} (1)

6. Generate the next generation by applying the GA operators.
   - Selection: Maintain 10% of the models with good results (lowest F function value).
   - Crossover: Use a uniform crossover operator to significantly accelerate the convergence.
   - Random the bit of single gene to a mutation.

The program will finish when the results meet the requirements or overlap with the number of loops. After the above process, a unit cell of a wideband FSS as a stopband structure is created with a length and width of \( L_p = W_p = 12.7 \text{ mm} \) and a thickness of 0.8 mm, as shown in Fig. 3, respectively.

In RGA, the selection of the values of the optimization parameter \( N_{par} \), the population size \( N_{pop} \), the crossover probability \( P_{cross} \), and the mutation probability \( P_{mut} \) are very important. These values will determine the convergence performance and the efficiency of the attainment of the optimum solution. In the RGA adopted in this study, \( N_{par} = 6 \) and \( N_{pop} = 50 \). The convergence criterion was set as small as possible [the value computed in equation (1)]. \( P_{cross} = 0.9 \) and \( P_{mut} = 0.1 \), respectively. The considered frequency range from 1 GHz to 10 GHz with the total number frequency points was 1,000. At this time, the optimization was terminated after 100 generations.

Fig. 5 (a) shows the convergence behavior of the RGA. Note that the best value (which satisfies the convergence criterion and the design requirements) of the fitness function was reached by the 42nd generation. Fig. 5 (b) compares the synthesized results at the initial, 20th, and last (42nd) generations with respect to the value of the transmission coefficient \( S_{21} \).

The design specifications were set up with the incident wave as the TE polarized wave, and the angle of the incident was set as that of a normal incident \( (\theta = 0^\circ) \). On average, each generation in the RGA simulation took about 3 min and 5 sec. The CPU time of the entire simulation process was 7 h and 35 min. It must be noted that the RGA used in this study was able to obtain the true profiles with a lower number of generations.

Table 1 compares the performance of this study to that of earlier studies. Fig. 6 plots the transmission coefficient of the FSS unit cell versus the frequency, with the elevation angle as a parameter for the TE and TM polarizations, respectively. In the figure, it is clearly visible that the designed FSS has a relatively stable frequency response with respect to the oblique incidence angles.

As mentioned, the substrate dimension was selected randomly and assumptively from several trial models. In the next step,
to define the optimal value of the compact property of the overall structure and to obtain the highest performance level, a deep study of this parameter was implemented. Fig. 4 shows that the range of values of \( L_g = W_g = 12.9 \) mm, \( 13.2 \) mm, and \( 13.7 \) mm corresponded to the spacing parameters between the adjacent cells of \( 0.2 \) mm, \( 0.5 \) mm, and \( 1 \) mm, respectively. From the figure, it can be seen that with a large spacing value, the resonant frequency and the reflection phase increased, and the bandwidth of the FSS stopband gradually became narrower. Therefore, the optimal design for the FSS reflector was chosen as that with \( L_g = W_g = 12.9 \) mm. Fig. 7 shows the surface current distribution of the FSS unit cell at the frequencies of \( 3.5 \) GHz, \( 5.2 \) GHz, and \( 5.8 \) GHz, respectively. The results exhibited a transmission coefficient (\( S_{21} \)) of \(-48.5 \) dB and a stopband bandwidth (when \( S_{21} < -10 \) dB and the reflection phase was \( \pm 90^\circ \)) of \( 5.5 \) GHz from \( 2.6 \) GHz to \( 8.1 \) GHz, which produced \( 105\% \) of impedance bandwidth with respect to the central frequency of \( 5.2 \) GHz. The results prominently show that the proposed FSS can be used to improve the antenna performance.

III. APPLICATION OF FSS ON ANTENNA PERFORMANCE

For the purpose of studying the ability of the FSS to improve the antenna performance, the proposed FSS structure was combined with the next model to achieve a perfect combination structure. Before the integration was set up, the layout of the broadband antenna based on M-shaped monopole structure was designed. As shown in Fig. 8 (a) and (b), the M-shaped antenna with a feeding line was etched on one side of a \( 0.4\) mm-thick FR-4 epoxy substrate with a relative permittivity of \( \varepsilon_r = 4.4 \) and a loss tangent of \( 0.02 \), and the other side had a partial T-shaped ground plane.

In this study, the FSS was located under the antenna to act as a stopband filter (called the “FSS reflector antenna”), as presented in Fig. 8 (c) and (d). It was found that the gain of the antenna in the existence of the FSS reflector would be maximum when two components [the round-trip free space propagation phase delay between the antenna and the FSS reflector in the R-plane (\( \varphi_R \)) and the reflected back-radiated waves from the antenna toward the FSS (\( \varphi_S \))] were added in the phase, which triggered a rise in the constructive interference [19]. The evaluation of the phase at the reference T-plane is depicted by the following equation:

\[
\varphi_T = \varphi_S + \varphi_R, \tag{2}
\]

with

\[
\varphi_R = 2 \times \frac{2\pi r \varphi}{c} Z. \tag{3}
\]

It must be noted that for the phase coherence, \( \varphi_T \) should be equal to zero or an integral multiple \( 2\pi \) at all frequencies. As shown in (3), the antenna-back-radiated \( \varphi_R \) will increase with the augmentation of the frequency and be controlled by the spacing \( Z \). In this study, the spacing between the antenna and the FSS layer was analyzed to obtain the excellent radiation characteristics.

![Fig. 8. Geometry of the antenna. [(a) and (b)] Antenna top and back views. [(c) and (d)] Top and side views of the antenna with the proposed FSS, with the operating mechanism.](image)

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<th>Table 2. Geometrical parameters of the M-shaped antenna</th>
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![Fig. 9. Impact of varying numbers of FSS unit cells on (a) the reflection coefficient and (b) the gain of the antenna.](image)
Besides, the dimensions of the FSS unit cell limit the size of the combination antenna. Hence, an in-depth analysis of the effects of the designed FSS on the antenna performance was conducted, the results of which are presented in Fig. 9, in which the reflection coefficients and the gains of the proposed structure are reflected with various amounts of unit cells. In the figure, it is implied that as the number of unit cells increased, the gain improved across the bandwidth, and the FSS reflectors slightly influenced the value and form of the reflection coefficient. Finally, the stage used with the optimal distance of \( Z = 20 \text{ mm} \) and the number of \( 6 \times 6 \) unit cells were selected, which provided the compactness property and a comfortable results response for the entire bandwidth. Then, to achieve the miniaturized size, the wider bandwidth and the higher gain of the antenna, all parameters of the final antenna, had to be optimized. The optimal dimensions of the parameters in mm are given in Table 2, and Fig. 10 shows the fabricated prototypes.

To validate the advantages of the proposed structure, the final prototype was experimentally characterized. Fig. 11 shows the measurement setups for the S-parameter with an HP 8719D vector network analyzer and the setup of the radiation pattern in a microwave anechoic chamber.

The reflection coefficients of the antenna alone and the antenna with the FSS reflector are shown in Fig. 12. It can be seen in the figure that the measured -10dB impedance bandwidth was 96.1% (3.1–8.1 GHz) for the antenna without FSS and 98.07% (3.3–8.4 GHz) for the antenna with FSS. The resonant frequency of the combination antenna slightly increased due to the loading of the FSS reflector. In addition, the measured gains of both structures with and without FSS are shown in Fig. 13. The maximum gains of the antenna with the FSS reflector were 9.8 dBi, 10.1 dBi, and 9.1 dBi at the frequencies of 3.5 GHz, 5.2 GHz, and 5.8 GHz, respectively.

For the whole band, the antenna performance enhancements due to the application of the proposed FSS were evident. For instance, in the 3.5GHz band, the enhancement was 7.8 dBi, while in the 5.2GHz and 5.8GHz bands, the enhancements were 7.1 dBi and 6.9 dBi, respectively.

The slight differences in the improvements are due to the optimal distance between the FSS structure and the antenna source. Fig. 14 shows the electric field distributions of the antenna with and without the FSS reflector at the frequencies of 3.5 GHz, 5.2 GHz, and 5.8 GHz. From the analysis of the results, it was clearly observed that after the FSS reflector was
implanted, the energy distributions of the electric field on the antenna source became stronger than in the case without FSS. This implies that the E-field direction at the corresponding resonant frequency tilted the FSS layer towards the opposite direction of the antenna. Thus, the designed FSS played a key factor in the antenna directivity and gain.

Moreover, the radiation patterns at 3.5 GHz, 5.2 GHz, and 5.8 GHz of the E-plane and the H-plane are plotted in Fig. 15. The antenna without an FSS reflector was bidirectional in the E-plane and quasi-omnidirectional in the H-plane. After the FSS structure was used, the radiation patterns became more directional and the back lobes were minimized by >12 dBi. Besides, in the case of the antenna alone, the E-plane beam was almost flat around the broadside direction with a maximum of 25°, whereas the maximum was along the broadside 0° in the case of the antenna loaded with an FSS reflector. As a consequence, the radiation pattern and the directivity of the antenna significantly improved after the FSS application. Finally, Table 3 shows a summarized performance comparison of this study with the most relevant studies reported in literature.

As shown in Table 3, the proposed structure exhibited much better performance in the context of the gain enhancement, bandwidth, and overall size that corresponded to the operating region. For instance, in [21] the slot antenna backed by the rectangular patch FSS showed a gain enhancement of only 3 dBi for a peak gain of 4.87 dBi at 3.9 GHz. In [18], a 5.5GHz bow-tie-shaped dipole antenna was proposed, which combined with the regular FSS slots to significantly improve the 6.7dBi gain to a peak gain of 12.1 dBi, but it had the drawbacks of a narrow bandwidth and a high profile. Besides, an 86.38% broadband antenna was obtained using a double square-loop FSS stopband for a 5.14GHz slot antenna. Although the antenna had a wide impedance bandwidth, it had a low gain enhancement of 5.53 dBi and a small peak gain of 8.87 dBi, whereas our proposed antenna had a fairly high gain improvement of 7.8 GHz for a peak gain of 10.1 dBi and a wider bandwidth of 98.07%, with a center frequency of 5.2 GHz. The improvements were due to the excellent properties of the matrix square-patched FSS de-
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signed by the RGA, which provided a deep transmission coefficient (S21) value of –48.5 dB (105%) and offered an effective phase that exhibited constructive interference with the antenna back-radiated wave. Those qualities that could not be found with the fundamental design method make the designed FSS a candidate for applications that require a high-performance, high-gain, low-profile, and broadband antenna.

III. CONCLUSION

In this paper, an unusual high-performance but cost-efficient wideband FSS was designed with a GA and used to enhance the gain of a broadband monopole antenna. The performance of the proposed FSS was proven through a simulation and experimental measurement. In fact, by using the FSS as a reflector, the gain of the antenna improved by 7.8 dBi for a peak gain of 10.1 dBi within a wideband of 98.07% (3.3–8.4 GHz). Thus, for the whole band, the performance improvement of the antenna due to the application of the proposed FSS was proven. It was also observed that the tested antenna radiation pattern achieved significant directional reduction on the back radiation for both the E and H planes. Therefore, the proposed FSS presents a promising potential for several wireless communication system services that require a broadband antenna with high gain and a low profile, including WiMAX, WLAN, and C bands for satellite application.

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DucDung Nguyen received his B.S. degree from the School of Electronics and Telecommunications of Vinh University in Nghe An, Vietnam in 2018. He is currently pursuing an integrated M.S. and Ph.D. degree at the Department of Information and Communication, Materials, and Chemistry Convergence Technology of Soongsil University in Seoul, South Korea. His current research interests include high-gain antennas, power amplifiers, metamaterials, wireless power transfer, and biomedical implantable antennas.

Chulhun Seo received his B.S., M.S., and Ph.D. degrees from Seoul National University in Seoul, South Korea in 1983, 1985, and 1993, respectively. From 1993 to 1995, he was a technical staff member at the Massachusetts Institute of Technology (MIT) in Cambridge, MA, USA; from 1993 to 1997, an assistant professor at Soongsil University in Seoul, South Korea; from 1999 to 2001, a visiting professor at MIT; and from 1997 to 2004, an associate professor at Soongsil University. Since 2004, he has been a professor of electronics engineering at Soongsil University; and from 2011 to 2014, the chairman of the IEEE MTT Korea Chapter. He is the president of the Korean Institute of Electromagnetic Engineering and Science; dean of the Information and Telecommunications College of Soongsil University; and director of the Wireless Power Transfer Research Center supported by the Korean Government’s Ministry of Trade, Industry and Energy, the Metamaterials Research Center supported by Basic Research Laboratories through a grant by the National Research Foundation (NRF) of Korea funded by the Ministry of Science, ICT and Future Planning, and the Center for Intelligent Biomedical Wireless Power Transfer supported by NRF. His research interests include wireless technologies, RF power amplifiers, and wireless power transfer using metamaterials.