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Design of microstrip patch antenna using Fennec Fox optimization with SSRR metamaterial for terahertz applications

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Abstract

This paper presents the design of a microstrip patch antenna based on a Square Split Ring Resonator (SSRR). Wireless technology is switching from 4G to 5G due to the need to overcome limitations, such as low throughput, high latency and path loss. To increase data transfer speeds, the next generation of wireless networks uses 5G terahertz technology. The use of microstrip patch antennas in wireless technologies has increased significantly due to their low cost and simplicity of design as well as the ease of printed circuit board fabrication. However, in some cases their use is limited by low bandwidth, low gain and low throughput. To solve these problems, the Fennec Fox optimization algorithm is used. The algorithm allows you to optimize the length of the microstrip patch antenna resulting in increased gain and reduced return loss. Bakelite is used as a substrate. The width of the patch antenna is set according to the most suitable length selected. To increase the bandwidth and Voltage Standing Wave Ratio (VSWR), a square split ring resonator (SSRR) is used as a metamaterial. An evaluation of the designed microstrip patch antenna model with existing patch antennas was performed. The estimated values of the parameters of the proposed model were the following values: return loss –72.54 dB, resonant frequency 1.11 THz, achieved gain 15.25 dB, VSWR value 1.5646. The estimated values of the developed model exceed those of existing samples. Thus, the developed microstrip patch antenna using Fennec Fox optimization and square split ring resonator metamaterial shows better results in the terahertz range.

Keywords

wireless technology, gain, resonant frequency, microstrip patch antenna, MPA, square split ring resonator, SSRR

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Проектирование микрополосковой патч-антенны на основе метаматериала SSRR для терагерцового диапазона с использованием алгоритма оптимизации Fennec Fox

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Аннотация

Представлена конструкция микрополосковой патч-антенны на основе квадратного разъемного кольцевого резонатора (Square Split Ring Resonator, SSRR). Беспроводная технология связи переходит со стандарта 4G на стандарт 5G из-за необходимости снятия таких ограничений, как невысокая пропускная способность, большая задержка и потери на пути передачи данных. В следующем поколении сетей беспроводной связи для повышения скорости передачи данных применяется терагерцовая технология 5G. Применение микрополосковых патч-антенн в беспроводных технологиях значительно расширилось благодаря их низкой стоимости, простоте конструкции и процесса изготовления печатной платы. Однако в ряде случаев применение патч-антенн ограничивается малой полосой пропускания, небольшим коэффициентом усиления и низкой пропускной способностью. Для решения этих проблем используется алгоритм оптимизации Fennec Fox, который позволяет оптимизировать длину микрополосковой патч-антенны, усилить сигнал и снизить обратные потери. В качестве подложки использован бакелит. Ширина микрополосковой патч-антенны установлена в соответствии с наиболее подходящей выбранной длиной. Для увеличения полосы пропускания и коэффициента стоячей волны по напряжению (КСВН) в качестве метаматериала применен резонатор на основе SSRR. Выполнена оценка спроектированной и существующих моделей микрополосковых патч-антенн. Оценочные значения параметров предлагаемой модели составили следующие величины: обратные потери –72,54 дБ, резонансная частота 1,11 ТГц, достигнутое усиление 15,25 дБ, значение КСВН 1,5646. Полученные значения параметров разработанной модели превосходят показатели существующих образцов. Таким образом, разработанная микрополосковая патч-антенна с использованием оптимизации Fennec Fox и метаматериала на основе квадратного разъемного кольцевого резонатора показала лучшие результаты в терагерцовом диапазоне.

Ключевые слова

беспроводная технология, прирост, резонансная частота, микрополосковая патч-антенна, MPA, квадратный разъемный кольцевой резонатор, SSRR

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Introduction

In daily life, wireless connectivity is crucial and acts as the transmission medium for sending data or information wirelessly from one location to another [1]. This enables data interchange across Radio Frequency (RF) and microwave frequencies without using a conductor. Electromagnetic waves are the medium used in wireless communication to transport data among the sender and the recipient [2]. High-speed data transfer between various electrical devices is necessary for next-generation wireless communication [3]. Terahertz (THz) frequency band is a range of frequencies between 0.1 to 10 THz that might be used for high-speed data transfer [4]. The terahertz frequency range is currently generating a lot of attention because of its higher data rate, higher bandwidth, non-ionizing nature and excellent determination in wireless communication [5]. Its spectral range is situated between the RF and mid-infrared regions, which may accommodate bandwidths as high as hundreds of GHz.

In the future years, the THz frequency range will enable high-channel capacity, increased data speeds and excellent quality broadcast capabilities [6]. Emitting or receiving electromagnetic waves is the purpose of an antenna. Traditional microwave antennas, which are often employed in various real-world applications, lack some of the benefits that microstrip antennas can execute [7]. The most basic and widely used microstrip antennas are rectangular and circular patches. The patch antenna is a key component of the existing wireless communication system that has been essential in this development [8]. Microstrip patch antennas (MPAs) are smaller, lighter, cheaper, easier to make and more easily integrated into wireless communication and mobile radio applications than traditional microwave antennas [9, 10]. Their primary drawbacks are reduced gain and bandwidth which may be greatly increased using various ways.

Utilizing metamaterials is one of the key techniques, an artificial material unavailable in nature [11]. Its qualities are determined by its structure which can be elliptical, rectangular, triangular, circular, or any other form, rather than by the materials it is composed [12]. The magnetic permeability, electric permittivity and index of refraction for natural materials are often positive. However, some of the properties are negative in metamaterials, and they are referred to as Negative Index Materials and Left-Handed Materials [13]. Metamaterials are used in the development of ideal lenses, wave retarders, absorbers, cloaks, and antennas [14, 15]. A parameter-based metamaterial MPA is designed to increase the terahertz resonant frequency for diverse applications. Major contributions of the designed model are:

- Designing a MPA using an optimization algorithm with Square Split Ring Resonator Metamaterial for Terahertz Applications;
- Bakelite material is employed as a substrate in the MPA for its better dielectric constant and loss tangent;
- Dimensions of the MPA are optimally selected using the Fennec Fox optimization;

— The Square Split Ring Resonator (SSRR) is used as a metamaterial to enhance the antenna gain and bandwidth.

Literature Survey

Many MPAs based on metamaterials are developed to enhance the bandwidth and gain of the antenna. Some related articles that use metamaterial MPAs have been researched and reviewed here.

Sağık et al. [16] had designed metamaterial structures by using the Artificial Neural Network (ANN) approach for optimizing the gain and directivity of a microstrip antenna. The radiation curves of the antennas can be formed by orienting them in accordance with the power densities that achieves in a particular direction which has been previously established. Using the best metamaterial structure, it was intended to enhance the gain and directivity of MPAs based on this characteristic of antennas. The developed metamaterial structures interacted with the antenna to train the ANN approach is to predict the best suitable values for the antenna gain, frequency and directivity.

Guttula et al. [17] had developed a MPA via an improved metaheuristic algorithm using an optimization algorithm. In order to support the development of the solution spaces for antenna restrictions, an alternative approach has been developed in this study. Elephant Herding Optimisation with Distinct Scaling Factor, an improved optimization method that modifies the MPA parameters having being developed. By choosing the MPA substrate thickness, patch length, width and dielectric value, the designed work aimed to attain optimum antenna gain. At last, the designed model was verified in terms of gain, cost and efficiency analysis was conducted.

Suraj et al. [18] had performed an optimized metamaterials-based WiFi antenna based on a genetic algorithm. The MPA for International Safety Management applications is described in this study and includes SSRR components at the ground plane. The antenna properties were increased as necessary by including the metamaterials that have been physically engraved into the ground without altering its radiating patch. The left-handed activity of metamaterials influenced by the direct contact of SSRR with electric fields is frequently represented as shunt inductance and series capacitance. The developed metamaterials antenna produces an increased gain while shrinking in size after a genetic algorithm is included.

Shamim et al. [19] had introduced a high-speed terahertz applications model with the miniaturized wideband MPA. This model of wireless communication MPA has a 0.72 THz resonance frequency. This designed antenna consists of an impedance bandwidth of 37.50 % and 0.72 THz centre frequency with a 0.53 to 0.84 THz frequency range. Input impedance, input loss, Voltage Standing Wave Ratio (VSWR) and radiation patterns in the E-planes and H-planes are used to demonstrate the result. The designing and simulation were done by utilizing the finite difference time domain method and a simulator based on full-wave electromagnetic with the CST Studio suite.

Singh et al. [20] had designed MPA for Ultra-Wideband (UWB) applications with the Moth-Flame optimization algorithm. MPAs are designed to work in dual and multi-band applications due to their inexpensive price, lightweight and simple installation. The antenna performance was enhanced, while the material cost was decreased by using the liquid crystal polymer substrate with the appropriate geometrical parameters. The MFO-optimized antenna has a small dimension of 50 × 50 mm, which enhances antenna performance. The antenna working bandwidth was 3.1 GHz, and its 20 dB Return Loss (RL) covered UWB applications. Comparing the simulation results to the preceding approaches, the designed model shows better radiation pattern, impedance bandwidth, directivity and steady gain for the entire frequency spectrum.

Different versions with varied MPAs have been developed in THz frequency that ranges for various applications based on the materials examined above. They basically chose to create an antenna with a higher size or a narrower bandwidth. Further research is required in MPA to enable data transferring at THz frequency in wireless communication. Thus, the optimized MPA is created to increase data transmission bandwidth at THz frequency.

Design of an Optimized MPA

MPAs are inexpensive with a small profile that is simple to develop and they can be integrated with electronic devices. To construct a high-performance antenna, one must understand the various antenna parameters in-depth. These parameters include the radiating patch, loss tangent, feeding method, dielectric material thickness and constant value. The material used for the substrate is positioned with the same width and length as placed between the radiating patch and ground plane.

Fig. 1 demonstrates the metamaterial-based MPA for terahertz applications. Fig. 1 illustrates the structure of an MPA which contains a radiating patch on one side and a ground plane on the other. The substrate, feed line, and radiating patch make up the layout. By using the microstrip inset method, a rectangular patch is supplied. In this model, the radiator patch is generated on a Bakelite substrate which is a material with the specified parameters such as loss tangent of 0.0002 and a relative permittivity of 4.8 intended for the development. The Fennec Fox Optimisation chooses the patch antenna ideal length and breadth for radiating. Based on the optimally selected length and width, the slot length and width and the insert feed length and width are

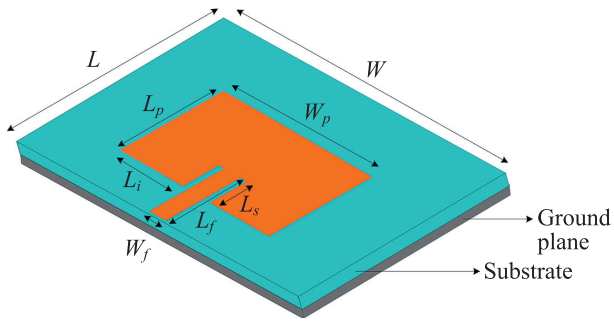

Fig. 1. Metamaterial-based MPA

determined for designing the metamaterial-based patch antenna. The metamaterial used in this model is a SSRR.

MPA parameters

The basic parameters used for designing the MPA are length (L), width (W) and height (H) of the substrate, length of the ground (L_g), microstrip feed width (W_p), inset feed width (W_f), inset feed length (L_f), slot length (L_s), width of the ground (W_g), slot width (W_s), and feed location (L_i). The patch antenna length and breadth have been determined best within these parameters corresponding to the fitness function of decreasing the resonant frequency. The resonant frequency is the frequency at which the patch receives the most power or when the feedline and patch impedances are most closely matched. It is also the juncture at which the impedance is purely resistive and inductive reactance equals the capacitive reactance.

$$\text{Resonant frequency, } fr = \frac{c}{2L\sqrt{\varepsilon_{reff}}}. \qquad (1)$$

Here, ε_{reff} denotes the effective dielectric constant, c denotes the speed of light in free space, and L signifies the length of the patch antenna.

Equations illustrated below are used to obtain the effective length and dielectric constant.

$$\varepsilon_{reff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(1 + \frac{12H}{W}\right)^{-0.5},$$

$$L_{eff} = L + 2\Delta L,$$

where ε_r represents the substrate dielectric constant; the patch antenna width, length and height are denoted as W, L and H.

Width of the microstrip patch antenna,

$$W = \frac{c}{2f_r}\sqrt{\frac{2}{\varepsilon_r + 1}}.$$

These parameters are determined for designing the MPA with minimal RL. The patch height is optimally selected using the Fennec Fox optimization algorithm.

Fennec Fox optimization algorithm

Fennec foxes are found in North Africa and Egypt's Sinai Peninsula as members of the Vulpes family of foxes [21]. Because of its huge ears, the fennec fox can be easily recognized. An omnivorous creature that consumes fruits, certain tubers, small birds, skinks and eggs. The fennec fox has two more significant qualities than its other abilities. These qualities include an effective digging ability and a means of avoiding predators. The two abilities of the fennec fox's behaviours are much more important than the rest of them. Some of these characteristics include the ability to dig deeply and the capacity to escape from predators. Fennec foxes build their nests in the sand, and they immediately dig their prey out of the sand after detecting their movements beneath because they are sensitive to the motions of tiny animals and insects.

Parameter optimization for the MPA

For selecting the optimal width and length of MPA, the Fennec Fox optimization algorithm is used. Some of the steps that are considered for optimal length and width are initialization, fitness function evaluation, updating and termination.

Step 1: Initialization. The optimal values for the width and length of the MPA are selected by initializing the values ranging from 90–120 μm. These values are initialized according to the following equation.

$$F = (X_1, X_2, X_3, \ldots, X_n).$$

Step 2: Fitness Function. Fitness function for the optimal value selection of length for the MPA is illustrated in the below equation.

$$fitness = \{\text{maximize}(f_r)\}.$$

By maximizing the resonant frequency of the MPA using the equation (1), the length can be optimally selected.

Step 3: Updating. Similarly, until the optimal solution is found, the various length values are updated using the below equations.

$$Z_a^{rand}: Z_{a,b}^{rand} = Z_{L,b},\ L \in \{1, 2, 3, 4, 5, \ldots, N\},$$

$$i = 1, 2, 3, 4, 5, \ldots, N$$

$$Z_{a,b}^{p2} = \begin{cases} z_{a,b} + r \times (Z_{a,b}^{rand} - I \times z_{a,b}),\ G_a^{rand} < G_a; \\ z_{a,b} + r \times (z_{a,b} - Z_{a,b}^{rand}),\ \text{else}, \end{cases}$$

$$Z_a = \begin{cases} z_a^{p2},\ G_a^{p2} < G_a; \\ Z_a,\ \text{else}, \end{cases}$$

where, G_a^{rand} is the objective function value, $z_{a,b}^{p2}$ and $Z_{a,b}^{rand}$ are its b^{th} dimension, Z_a^{rand} denotes the escape of the a^{th} Fennec Fox from the intended target position, z_a^{p2} signifies the new suggested status for the second phase of the a^{th} Fennec Fox, G_a^{p2} represents the objective function value, and I signifies the random number.

Step 4: Termination. After the attainment of best solution, the process will get terminated. Based on the optimally selected length of the MPA, the width of the MPA can be determined and both are simulated for evaluating the performance of the model.

Experimental analysis of designed MPA

MATLAB and HFSS tool are used to create the metamaterial-based MPA for evaluating this proposed model. The Finite Element Method (FEM) is the most widely used commercial FEM for electromagnetic structures in HFSS tool. To correctly optimize the antenna settings, this is particularly beneficial for antenna engineers. The Intel i5-10th Gen processor, CPU @ 2.50 GHz, NVIDIA GTX 1650 4 GB (GDDR6) GPU, 16 GB Memory (RAM), and 64-bit operating system are used to perform the testing. The designed MPA using the ANSYS HFSS tool is illustrated in Fig. 2, *a*.

Fig. 2, *b* illustrates the MPA in this model which is based on the SSRR [22] metamaterial with the 3 × 3 unit cell structure. For optimally selecting the length of the

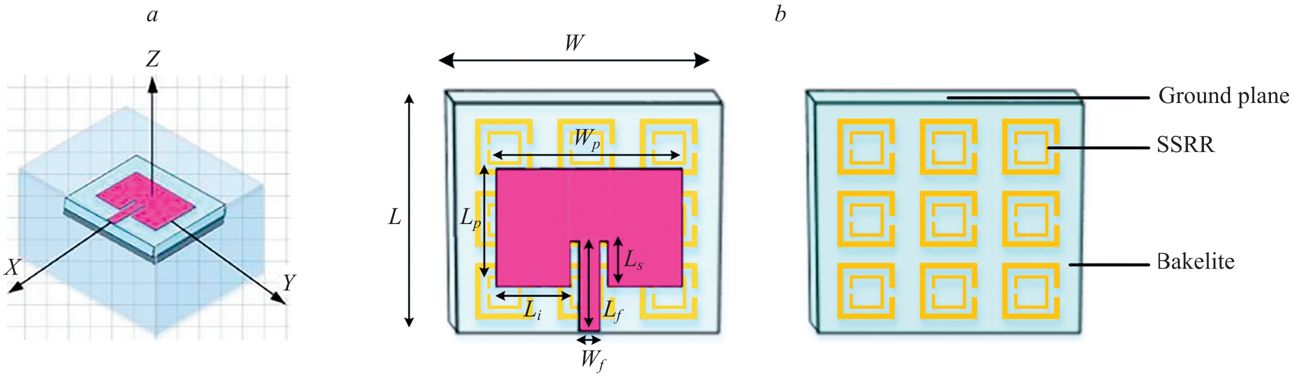

Fig. 2. The developed model of the MPA (*a*) and the design of the MPA based on the SSRR metamaterial (*b*)

Table 1. Parameters for designing the MPA

Parameter	Dimensions, μm
Length of the substrate L	150
Width of the substrate W	180
Height of the substrate H	10
Length of the ground L_g	150
Width of the ground W_g	180
Length of the patch L_p	90 (optimally selected)
Width of the patch L_w	120
Microstrip feed width W_p	5
Slot length L_s	40
Inset feed length L_f	98
Slot width W_s	50
Inset feed width W_f	20
Gaps between the ring $g1$	0.1
Gaps between the ring $g2$	0.2
Spacing between the rings	0.2

micro patch, the Fennec Fox optimization algorithm is used. Based on this optimally selected length, the other designing parameters for the MPA are determined.

Table 1 illustrates the derived parameters for designing the MPA with SSRR metamaterial. Analysing the MPAs RL, both with and without metamaterial allows for a more accurate evaluation of the intended model. While evaluating an antenna RL performance, maximum transfer of power theory and impedance matching are an essential factors. They measure the efficiency with which an antenna transfers electricity from an electrical source to an antenna. The proportion of the incident antenna power to the power p_{in} reflected back from the source antenna p_{ref} is known as the RL.

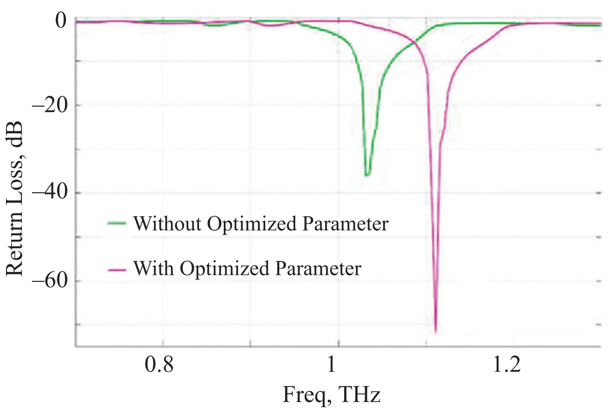

Fig. 3. Return loss for with and without optimized parameter-based proposed patch antenna

Fig. 3 illustrates the RL of the MPA with and without optimized parameter. The metamaterial surface is built using a Split Ring Resonator in the shape of a square. The proposed SSRR is made up of two concentric square rings with an outer and inner radius square with a thickness of 5 μm. The metallic component is produced by printing on a Bakelite substrate. The achieved RL of with and without optimized parameter for 1.04 THz and 1.11 THz are –36.50 dB and –72.54 dB, respectively.

Refractive index with real and imaginary graph of optimized parameter based patch antenna is illustrated in Fig. 4, *a*. The refractive index of the SSRR is negative-index metamaterial whose refractive index for an electromagnetic wave has a negative value over some frequency range. Negative permittivity and permeability are produced by the metamsaterial as a result of the negative refractive index value. The refractive index of the proposed SSRR is –4 for the frequency 1.06 THz. Fig. 4, *b* illustrates the RL for proposed optimized length parameter compared with the different length parameter of the patch antenna. The proposed optimized parameter is 90, which is compared with the different parameters of the patch antenna that are 75, 80, 85, 95, 100 and 105. The attained RL for the proposed and different parameter values are 38 dB, 43 dB, 46 dB, 72 dB, 56 dB, 60 dB and 65 dB for the frequency of 1.1 THZ to 1.14 THz.

As illustrated in Fig. 5, the degree of directivity of the antenna radiation pattern is known as antenna gain. It is equivalent to the sum of the electrical effectiveness and directivity of the antenna. The maximum obtained gain antenna for with and without optimized value are 2.44 dB and 15.25 dB. Thus, from these attained gain values, the optimized parameter values of the MPA works with greater than the without optimized parameter value.

Fig. 6 shows RF electrical transmission system, the VSWR is the proportion of transmitted to reflected voltage standing waves. VSWR is the more popular term for SWR

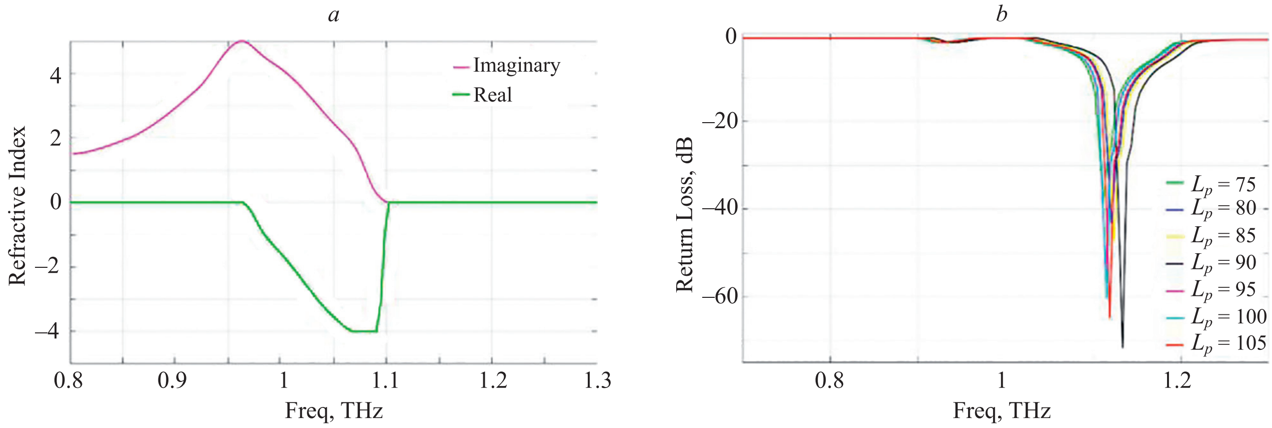

Fig. 4. Refractive index of a patch antenna with optimized parameters (*a*) and comparison of return losses for patch antennas of different lengths (*b*)

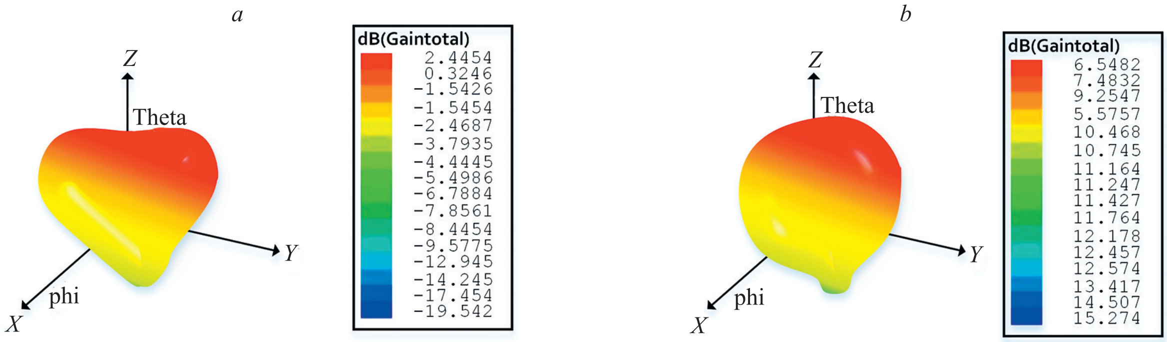

Fig. 5. Gain of an antenna for with (*a*) and without (*b*) optimized value

because it frequently signifies the voltage ratio. The VSWR value obtained for the proposed model at a resonance frequency of 1.11 THz equals to 1.5 and the VSWR value of 2 were determined at 0.90 and 1.25 THz, respectively.

Transmission coefficient compares the amplitude of the transmitted wave to that of the incident wave. It is described as the ratio of the amplitudes of the transmitted and incident voltage waves. Reflection coefficient compares the amplitudes of the incident and reflected waves. It is described as the ratio of the amplitude of the incoming voltage wave to that of the reflected voltage wave. In Fig. 7, the transmission and reflection coefficient of the proposed patch antenna are illustrated. The transmission curve steepens at 1.09 THz, the same frequency at which the reflection curve peaks. This suggests that a resonance exists at 1.10 THz. The periodic arrangement of each unit cell causes it to function as a microwave resonant circuit.

MPAs are designed based on various substrate materials with different dimensions, which are illustrated in Table 2. For comparison, the proposed model is evaluated for RL, resonant frequency, gain and VSWR. The existing methods compared with the proposed model are FR4 [18], Roger RT Duroid 5880 [10], Silicon Oxide [20] and Quartz [21]. From the comparison of the proposed and existing model,

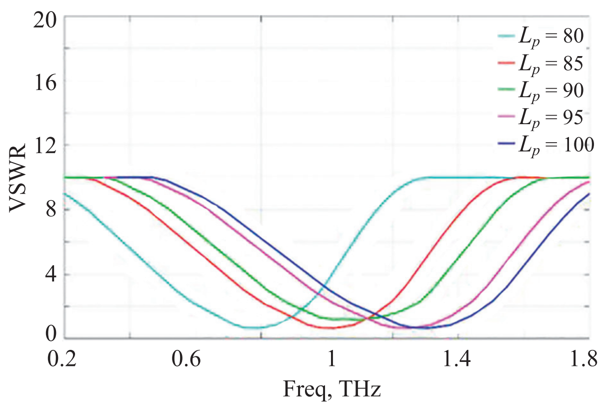

Fig. 6. VSWR comparison for different length of the patch antenna

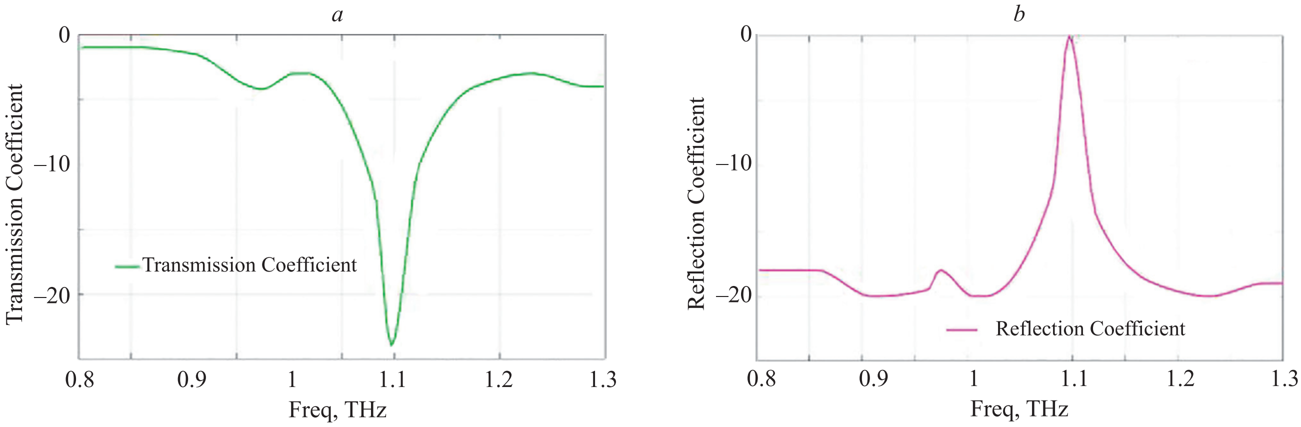

Fig. 7. Transmission (*a*) and reflection (*b*) coefficients for the proposed model

Table 2. Comparison of proposed and existing micro strip patch antenna

	Proposed optimized patch antenna	Palanivel Rajan and Vivek [23]	Darboe et al. [24]	Ghosh and Mitra [25]	Sirmaci et al. [26]
Substrate	Bakelite	FR4	Roger RT Duroid 5880	Silicon Oxide	Quartz
Size, mm^2	0.15 × 0.18	8 × 8	6.285 × 7.235	—	0.18 × 0.212
Patch size, mm^2	0.90 × 0.120	1.025 × 1.58	3.4 × 4.1	0.136 × 0.189	0.92 × 0.152
Resonant frequency, THz	1.11	0.074	0.028	0.46	1.08
RL, dB	–72.54	–15	–13.48	–17.08	–55
VSWR	1.5646	1.148	1.5376	1.024	1.00
Gain, dB	15.25	10.81	6.63	9.64	3.57

the attained parameter values of the model are better than the existing antenna model.

Conclusion

Using the Ansys HFSS tool, the design and analysis of the MPA are implemented and evaluated. The bakelite material serves as the substrate for the design of the MPA and the patch antenna length is determined using the Fennec Fox optimization method. To increase the bandwidth of the developed model, the SSRR is employed as the metamaterial. The designed model is evaluated by resonant frequency, return loss, gain, and VSWR. These evaluated values are compared with the existing techniques with different patch size and substrate, such as FR4, Roger RT Duroid 5880, Silicon Oxide and Quartz. The attained RL values of the proposed and existing model are –72.54, –15, –13.48, –17.08 and –55. Likewise, the resonant frequency, gain and VSWR of the proposed and existing model are evaluated and compared. Based on these attained values, the proposed model results in greater values than the existing designed MPA. Thus, the design of MPA using Fennec Fox optimization with SSRR metamaterial performs better than the existing metamaterial based MPA. In future, the designed MPA can reduce more RL and enhance the resonant frequency with maximum gain.

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