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REGULAR ARTICLE

Bandwidth Enhanced and Gain Improvement of Compact Patch Antenna Using Metamaterials for UWB applications

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A compact new ultra-wideband (UWB) antenna using planar metamaterial (MTM) structures is proposed. The antenna is designed with a double-side planar periodic cell structure. The proposed 3-D unit cell show an artificial negative electric permittivity medium (NEPM), exhibiting a wide electromagnetic band-gap (EBG) created by etching four L-shaped slots on the main square patch and crossed-shaped slots on the ground plane. The proposed antenna fabricated on a 1.52 mm low-cost Rogers RO4003C substrate, is compact, measuring 22.4 × 25.6 mm², with a relative permittivity of 3.38 and a loss tangent of 0.0027. It has a broad bandwidth covering 3.8 GHz to 17.7 GHz, relatively 129%. The average gain over the entire bandwidth is 5.44 dB, with a peak value of 8.55 dB at 15.5 GHz. Design and simulation were carried out using the finite integration technique (FIT)-based CST microwave studio. The measured return loss (S_{11}) of the prototype was in good agreement with the simulated results. The proposed antenna shows satisfactory radiation efficiency, achieving between 80% and 93% over the whole band. The measured gain of the test antenna demonstrates favorable radiation characteristics and shows the stability of radiation patterns at low frequencies. A comparative study with the related literature reviews recently published highlights the compactness of our MTM antenna configuration, presenting a reduction factor between 43.13% and 56.25%. Due to its outstanding performance, the proposed design is positioned as a strong candidate for various UWB applications, and also can be used for satellite communications and radar applications.

Keywords: UWB, Compact Antenna, Metamaterial, Unit Cell, EBG, Negative Permittivity, NEPM.

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1. INTRODUCTION

The rapid development of telecommunication systems has facilitated the creation and innovation of several technologies. On one hand, there is a trend towards the miniaturization of components related to mobile devices; on the other hand, there is an increasing demand for fast data transfer, which alternatively requires broadband and multiband components. These two contradictory constraints must be addressed with inexpensive solutions that provide high efficiency. The utilization of Ultra Wideband (UWB) technology [1] emerges as one of the best solutions, offering a high data transfer rate while maintaining limited complexity and costs. In recent years, the deployment of this technology, especially in mass-market applications, necessitates the use of miniature UWB antennas, at low-cost and high performance [2]. Moreover, designing a compact size of antenna with good characteristics poses a challenging task for researchers. Metamaterials appear to be a promising solution to address these challenges by reducing the size and increasing the bandwidth of planar antennas. The term "Metamaterials" generally refers to artificial composite materials exhibiting extraordinary electromagnetic properties not found in nature [3].

These materials are typically periodic, dielectric, and metallic structures. Due to the induced electric and/or magnetic resonance of MTM unit cell, exotic effective constitutive parameters can be realized, such as split ring resonator (SRR) [4] and periodic structures built of very thin wires [5]. Obtaining unusual values for permittivity and permeability opened avenues for reducing radiating element size [6], controlling couplings within large networks [7], and operating in multi-band and broadband frequencies [8].

EBG MTM structures have the property to suppress electromagnetic wave propagation (stop-band) within specific frequency ranges [9]. Recently, EBG structures have been applied in diverse ways in microstrip antennas, including the suppression of surface waves [10] and enhancement of antenna radiation performance [11, 12]. Moreover, the inclusion of active elements in the EBG material on which the antennas are placed can be used to improve the antennas performance by achieving a reconfigurable radiation pattern [13].

In this paper, a MTM unit cell considered as an artificial medium with negative electrical permittivity (NEPM), exhibiting wide electromagnetic band-gap (EBG) is presented. Also, a compact UWB antenna using the MTM concept is designed, to enhance the antenna gain and bandwidth by etching the proposed MTM unit cell arranged in a 2D pattern on the radiating element

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and on the bottom ground plane. The proposed UWB antenna covers the C-band, X-band, and Ku-band.

2. EBG UNIT CELL DESIGN AND SIMULATION

EBG structure is one of the Metamaterials, exhibit an electromagnetic band-gap (EBG) in a particular frequency band. It is formed from unit cells composed of conductors and dielectrics arranged periodically in 2-D or 3-D, whose unit cell dimensions are very small compared to the wavelength, and can be treated as a homogeneous material in good approximation. Then, it is possible to analyze this material as an effective medium, where its properties are not found in any known natural material [3-5]. A common drawback of EBG MTMs structures is that their properties are limited to narrow frequency bands [14]. This work presents a new geometric configuration for EBG unit cell exhibiting a broadband-gap. A two-dimensional dual-band resonator elementary cell is designed using two conductive copper layers 17.5 μm thick etched on a square dielectric substrate: the Rogers RO4003C ($\varepsilon_r = 3.38$, tg$\delta = 0.0027$), with a thickness of 1.52 mm as shown in Fig. 1(a), (b) and (c). The upper face features a square patch with four L-shaped slots on the four sides, while the lower face represents the mass with crossed-shaped slots. The 3-D unit cell was modeled on the CST software based on a frequency domain solver and all cell dimensions were optimized to ensuring a wide band gap to extend the bandwidth as much as possible of the proposed UWB antenna. The unit cell dimensions are given in Table 1.

Table 1 – Parameters of the proposed MTM cell

Parameter	Dimension (mm)	Parameter	Dimension (mm)
$L_s = W_s$	3.2	g_2	0.4
w_1	1.2	w_2	0.8
g_1	0.2	l_1	1

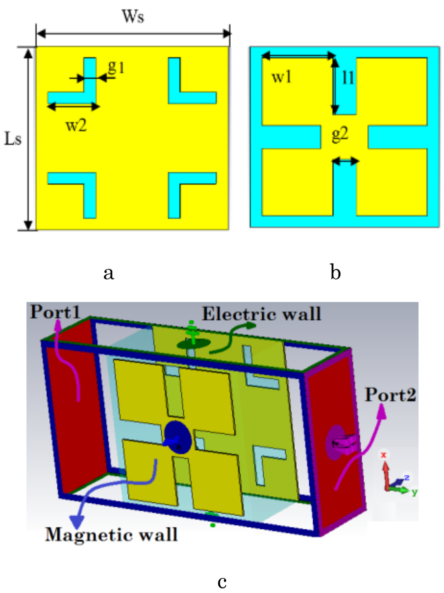


Fig. 1 – Planar view of the elementary cell: (a) upper face, (b) lower face, (c) cell modeling on CST with boundary setup

The proposed metasurface cell was located between two waveguide ports on the positive and negative y-axis. The boundary conditions for the x- and z-axes were set to perfect electric conductor (PEC) and perfect magnetic conductor (PMC), respectively, as illustrated in Fig. 1c. The effective parameters of the unit cell are retrieved by S parameter method [15], utilizing the normal incidence and scattering parameters (S_{11}, S_{21}) of the homogeneous material. From the CST microwave studio, all complex effective parameters are extracted, such as effective impedance Z, refractive index n, magnetic permeability μ and electric permittivity ε.

The values of refractive index n and impedance Z can be determined from equations (2.1) and (2.2) [16].

$$n = \frac{1}{kd}\cos^{-1}\left[\frac{1}{2S_{21}}\left(1 - S_{11}^2 + S_{21}^2\right)\right], \quad (2.1)$$

$$Z = \sqrt{\frac{\left(1+S_{11}\right)^2 - S_{21}^2}{\left(1-S_{11}\right)^2 - S_{21}^2}}, \quad (2.2)$$

Where d, is the maximum length of the unit cell, and k is the wave number in free space.

The effective values of permittivity ε and permeability μ can be determined as (2.3) and (2.4), respectively:

$$\varepsilon = \frac{n}{Z}, \quad (2.3)$$

$$\mu = nZ, \quad (2.4)$$

Fig. 2 shows the amplitude (in dB) of the transmission and reflection coefficients of the elementary structure. The unit cell resonates in two frequency bands: one at 13.45 GHz and one at 20.3 GHz, Notably, the transmission coefficient S_{21} approaches zero outside these bands, effectively impeding the propagation of electromagnetic waves within the structure. The rejection band of the structure, which was designed to correspond to –3 dB, is approximately 6.34 GHz, ranging from 13.76 GHz to 20.1 GHz, demonstrating the structure's electromagnetic band gap (EBG) behavior. A transmission peak of –15.9 dB is observed at 17.2 GHz.

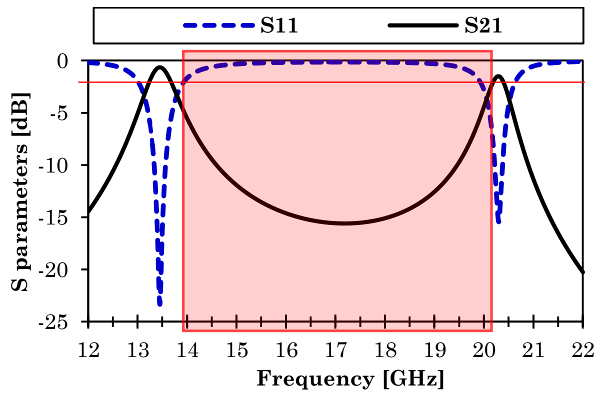
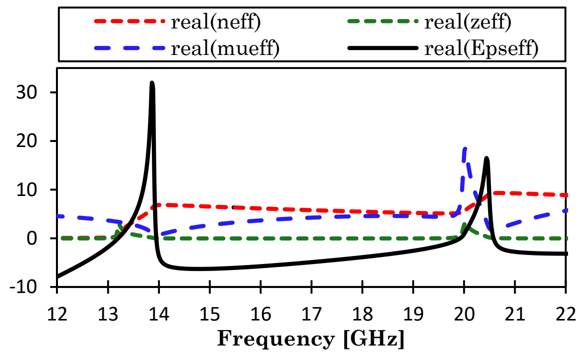


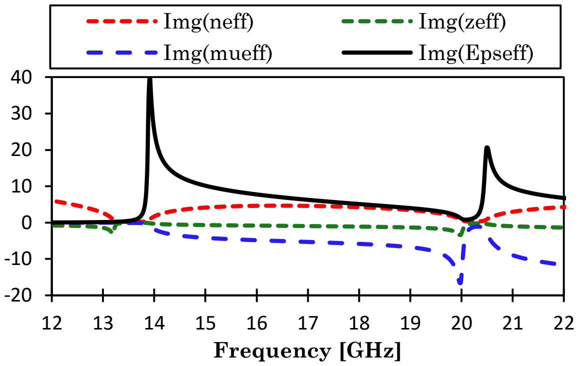
Fig. 2 – S parameters of the MTM cell

Both n and Z, and thus μ and ε, are frequency-dependent complex functions that satisfy certain requirements based on causality. For passive materials, it is essential that the real component of impedance Z and the imaginary component of refractive index n are greater than zero. Fig. 3a shows the real part of these effective parameters, where all are positive except the real part of ε is negative in the band-gap from 14 to 20 GHz and outside the two narrow bandwidths centered around 13.5 and 20.3 GHz, respectively. From Fig. 3b, the imaginary part of n is positive, guaranteeing that the medium is passive. The imaginary part of μ, indicating magnetic loss, is less than zero, while the imaginary part of ε, indicating electric loss, is greater than zero.

Based on these results, the proposed unit cell is considered as an artificial negative electrical permittivity medium (NEPM), exhibiting a wide electromagnetic band-gap (EBG).



a



b

Fig. 3 – Real and imaginary part of effective parameters: (a) Real part, (b) Imaginary part

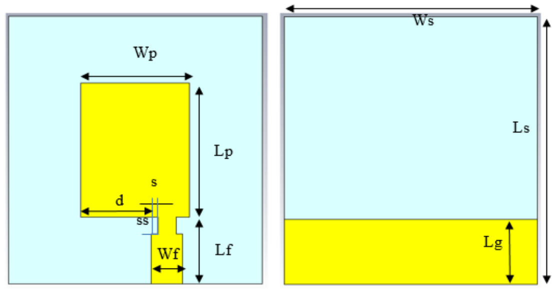
3. ANTENNA DESIGN AND CONFIGURATION

Particular EBG structures, such as two-dimensional arrays, can offer attractive properties for antennas [10-12]. The rectangular microstrip patch antenna presents a novel structure based on the electromagnetic band-gap (EBG) structure using MTM technology and is designed with a double-side planar periodic cell structure.

Initially, a rectangular planar monopole antenna with a partial ground plane was chosen as the base antenna. It is fed by a microstrip line, utilizing a short section of the transmission line to match 50Ω, as illustrated in Fig. 4. The same substrate of size 22.4 × 25.6 mm² as before was used. Fig. 5 depicts the configuration of the proposed MTM antenna. In this setup, the metasurface cell studied previously was applied to demetalize the patch and metalize the ground plane, resulting in a two-dimensional periodic structure. The optimized parameters of the proposed antenna are summarized in Table 2.

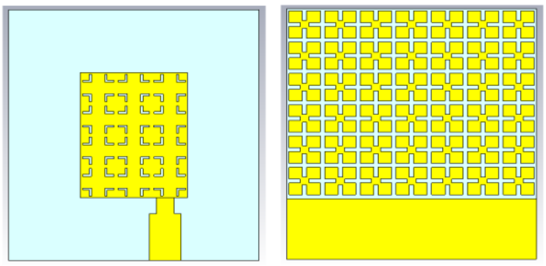
Table 2 – Optimized antenna parameters

Parameter	Size (mm)	Parameter	Size (mm)
L_s	25.6	L_f	6.4
W_s	22.4	L_g	6.2
W_p	9.6	d	6.2
L_p	12.8	s	0.6
W_f	2.8	ss	1.6



a b

Fig. 4 – Basic antenna: (a) Radiating patch (b) Ground plane



a b

Fig. 5 – Proposed antenna: (a) Radiating patch (b) Ground plane

4. RESULTS AND DISCUSSION

It was observed that the bandwidth of the proposed antenna is doubled compared to the base antenna. It achieved, at the level of –10 dB, a bandwidth ranging from 3.8 GHz to 17.7 GHz, for a total bandwidth of 13.9 GHz, while in the conventional antenna the bandwidth was 7.35 GHz, with improved impedance matching, as shown in Fig. 6. This indicates that the goal of achieving impedance matching over a wide frequency band has been optimally satisfied through the introduction of MTM's.

The gain of the main antenna increases from 1.2 to 5.5 dB with frequency, while the radiation efficiency varies from 66 to 88% within the operating band, as shown in Fig. 7. In Fig. 8, the gain of the proposed antenna achieved an average gain of 5.44 dB over the entire operating band and a maximum value of 8.55 dB at 15.5 GHz. Concerning the radiation efficiency, it varies between 80% and 93% over the working bandwidth. A comparison of these results with those of the base antenna reveals a notable improvement in gain and efficiency.

A comparative study of the proposed antenna with some existing similar antennas in terms of size, frequency of operation, gain and efficiency has been summarized in Table 3. These antennas are based on the same principle: antenna based on periodic MMA structures. Each antenna is designed to be compact and specifically suited for UWB applications. The size reduction achieved for our prototype antenna, compared to other structures in the literature, is calculated based on the reduction in area R_s:

$$R_s(\%) = \left(1 - \frac{S_f}{S_i}\right).100\%, \qquad (3.1)$$

where S_i is the area occupied by the reference antenna, and S_f is the area occupied by the proposed design.

As shown in Table 3, the size of the proposed design was reduced from 43.13% to 56.25%. This reduction in physical dimensions not only achieves a goal of size reduction but also contributes to improvements in gain and efficiency.

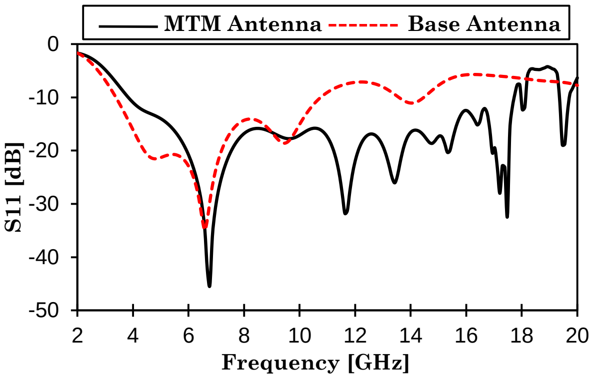


Fig. 6 – Reflection coefficient of the proposed and the base antenna

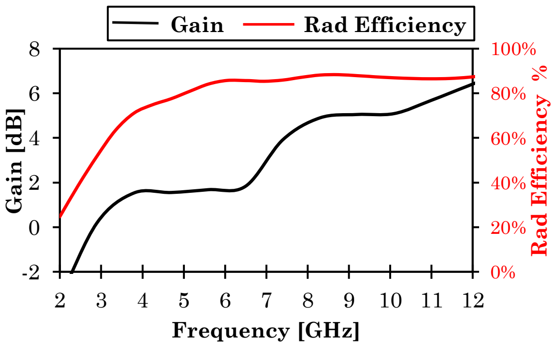


Fig. 7 – Gain and radiation efficiency of the base antenna

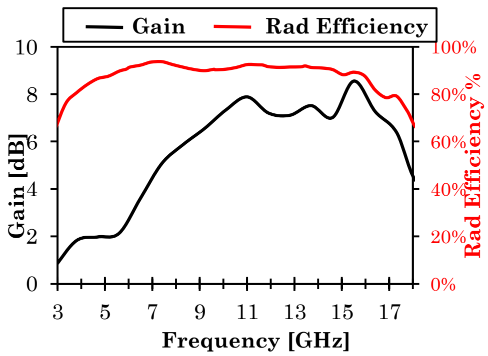


Fig. 8 – Gain and radiation efficiency of the proposed antenna

Table 3 – The comparison of several antennas

Ref.	Size (mm²)	Band-width (GHz)	Bandwidth (%)	Peak Gain (dB)	Peak Eff. %
[8]	32 × 28	3 – 36.4	169	8.02 at 19.4 GHz	80
[17]	31.8 × 27.6	4.1 – 19.4	130	8.2 at 11.7 GHz	89.7
[18]	31.8 × 27.6	3.3 – 17	135	6.9 at 12.2 GHz	--------
[19]	32 × 27.6	3.2 – 23.9	170	6.2 at 8.7 GHz	81
[20]	30.4 × 27	4 – 16.2	120	8 dBi at 9.2 GHz	--------
Our ant.	**25.6 × 22.4**	**3.8 – 17.7**	**129**	**8.55 at 15.5 GHz**	**93**

5. MEASUREMENTS AND DISCUSSION

To validate the simulation results, an experimental verification was conducted by fabricating the prototype illustrated in Fig. 9. The prototype was manufactured using a laser printer specifically designed for printed circuits, available in the RF laboratory at INRS in Montreal, Canada. The reflection coefficient was measured using a Vector Network Analyzer (VNA) also located in the same laboratory.

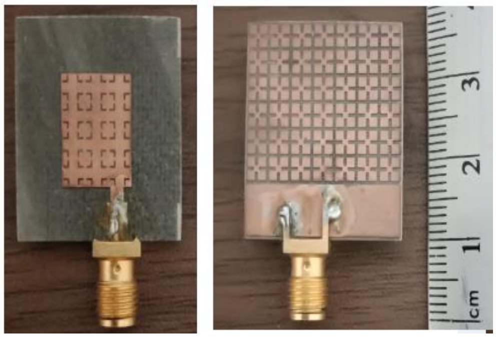


Fig. 9 – Prototype photograph of the proposed antenna

There is a satisfactory agreement between the simulation and measurement results of reflection coefficients, as illustrated in Fig. 10. The measured bandwidth spans from 3.98 GHz to 17.2 GHz, approximately 124%, while the simulated bandwidth is 129%, ranging from 3.8 GHz to 17.7 GHz.

The far-field radiation patterns of the proposed antenna were also measured in an anechoic chamber available at the same INRS laboratory, specifically at frequencies of 6.7 GHz, 11.6 GHz, and 17.2 GHz. The measurements were conducted in both the E and H planes for two polarization modes: Co-Polarization and Cross-Polarization. In Fig. 11, the normalized gain in dB is illustrated. It can be observed that the radiation pattern appears almost omnidirectional and remains stable at lower frequencies. However, some distortions are noticeable at higher frequencies, likely attributed to the experimental environment and reflections at the edges of the MTM periodic structure.

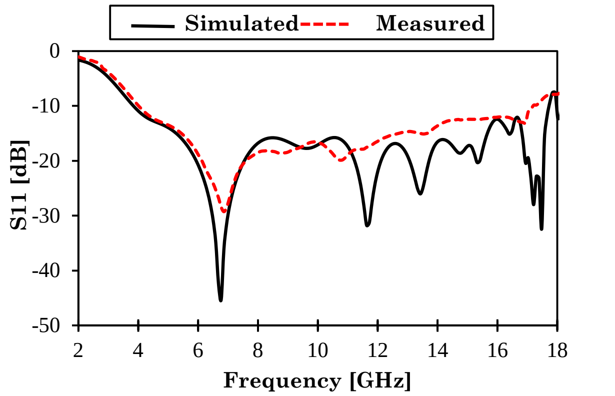


Fig. 10 – Results of measured and simulated values of S_{11} for the proposed antenna

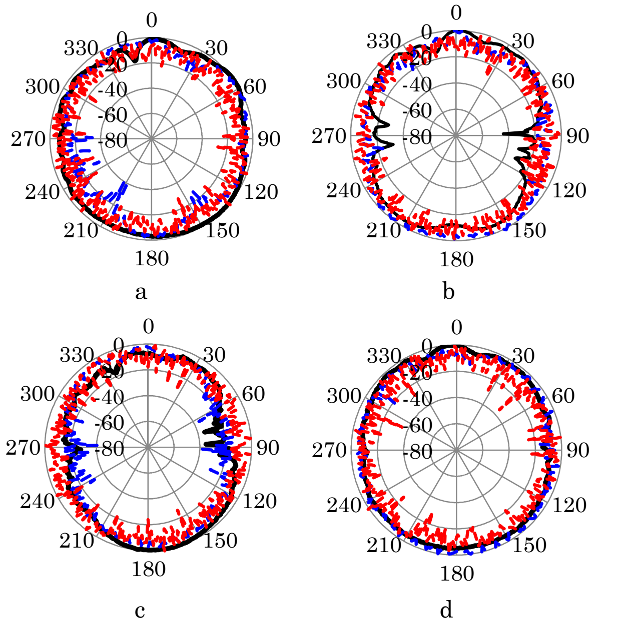


Fig. 11 – Measured gain of the proposed antenna for the frequencies: 6.7, 11.6 and 17.2 GHz: (a) Co-Pol E-Plane, (b) Cross-Pol E-Plane, (c) Co-Pol H-Plane, (d) Cross- Pol H-Plane

6. CONCLUSIONS

In this paper, an Ultra-wideband compact antenna utilizing the Metamaterial (MTM) concept of planar periodic cells was designed. The proposed unit cell exhibits an artificial negative electric permittivity medium (NEPM), effectively achieving a good stop-band phenomenon across a broad frequency spectrum. The performance results of the proposed antenna reveal a substantial increase in bandwidth, extending from 3.8 to 17.7 GHz, realizing a bandwidth of 13.9 GHz relatively 129%, with notable impedance matching. The antenna achieves high gain, reaching a maximum value of 8.55 dB at 15.5 GHz and maintaining an average value of 5.44 dB across the entire operating band. Enhanced radiation efficiency is demonstrated, ranging between 80% and 93%. This analysis underscores the potential of the proposed antenna as a promising solution for various UWB applications, including wireless communication systems, location-based applications, and even satellite and radar applications.

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Розширення смуги пропускання та посилення компактної патч-антени з використанням метаматеріалів для додатків UWB

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Запропоновано нову компактну надширокосмугову (UWB) антену з використанням плоских структур з метаматеріалу (MTM). Антена розроблена з двосторонньою плоскою періодичною осередковою структурою. Запропонована тривимірна елементарна комірка демонструє штучне середовище з негативною електричною проникністю та широку електромагнітну заборонену зону, створену шляхом гравування чотирьох *L*-подібних прорізів на головній квадратній ділянці та хрестоподібних прорізів на площині землі. Запропонована антена, виготовлена на недорогій підкладці Rogers RO4003C діаметром 1,52 мм, є компактною, має розміри 22,4 × 25,6 мм^2, з відносною діелектричною проникністю 3,38 і тангенсом втрат 0,0027. Він має широку смугу пропускання від 3,8 до 17,7 ГГц, що становить 129%. Середнє посилення по всій смузі частот становить 5,44 дБ з піковим значенням 8,55 дБ на 15,5 ГГц. Проектування та моделювання проводилися за допомогою мікрохвильової студії CST на основі методу кінцевої інтеграції (FIT). Виміряні зворотні втрати прототипу добре узгоджувалися з результатами моделювання. Пропонована антена демонструє задовільну ефективність випромінювання, досягаючи від 80 до 93% по всьому діапазону. Коефіцієнт підсилення тестової антени демонструє сприятливі характеристики випромінювання та стабільність діаграм спрямованості на низьких частотах. Порівняльне дослідження з нещодавно опублікованими оглядами відповідної літератури підкреслює компактність нашої конфігурації антени MTM, демонструючи коефіцієнт зниження від 43,13 до 56,25%. Завдяки своїй видатній продуктивності запропонована конструкція позиціонується як сильний кандидат для різноманітних додатків UWB, а також може використовуватися для супутникового зв'язку та радіолокації

Ключові слова: UWB, Компактна антена, Метаматеріали, Елементарна комірка, EBG, Негативна діелектрична проникність, NEPM.