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Design and Comparative Performance Analysis of THz Microstrip Patch Antenna Using ZEONEX® as a Polymer Substrate for 6G Applications

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Keywords:
Microstrip Patch Antenna.
6G.
3THz.
THz Band.
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ABSTRACT

This study presents the design and performance comparison of a microstrip patch antenna operating at 3 THz. The main contribution is to introduce and evaluate ZEONEX® (Cyclic Olefin Polymer (COP)) as a low-loss polymer substrate alongside various conducting patch materials. In this study, ZEONEX® was used as the common substrate, and the behavior of four metallic patch materials (silver, copper, gold, and aluminum) was analyzed using Computer Simulation Technology (CST) Studio Suite. The simulation results demonstrate the impact of the investigated conducting patch materials on the antenna's electromagnetic performance when combined with the ZEONEX® substrate. This combination achieved a stable resonance at 3 THz with a good voltage standing wave ratio (VSWR) of 1.07–1.11. Importantly, the designs demonstrate a wide bandwidth of 80 GHz and achieve high realized gain in the range of 7.01–7.28 dBi, which is comparable to reported values in previous THz antenna studies. These results indicate that ZEONEX® is a promising substrate material for THz antenna designs in next-generation communication systems.

تصميم وتحليل الأداء المقارن لهوائي ميكروستريب بتردد THz باستخدام ZEONEX كركيزة بوليمرية لتطبيقات الجيل السادس G6

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الكلمات المفتاحية:
هوائي رقعة الميكروستريب.
G6 الجيل السادس.
3تيراهيرتز.
نطاق التيراهرتز.
ZEONEX®.

الملخص

تقدم هذه الدراسة تصميمًا ومقارنةً في الأداء لهوائي رقعة ميكرو سترب يعمل عند تردد 3 تيرا هيرتز. تتمثل المساهمة الرئيسية في تقديم وتقييم مادة ® ZEONEX (البوليمر الأوليفيني الحلقي COP) كركيزة بوليمرية منخفضة الفقد إلى جانب مواد رقعة موصلة مختلفة. في هذا البحث، وباستخدام ® ZEONEX كمادة الركيزة المشتركة، تم تحليل سلوك أربع مواد معدنية للرقعة الألمنيوم، والنحاس، والذهب، والفضة باستخدام برنامج Computer Simulation Technology (CST) Studio Suite. توضح نتائج المحاكاة تأثير مواد الرقعة الموصلة المدروسة على الأداء الكهرومغناطيسي للهوائي عند دمجها مع ركيزة ® ZEONEX.حقق هذا الدمج رنينًا مستقرًا عند 3 تيرا هيرتز مع نسبة موجة واقفة للجهد (VSWR) جيدة تتراوح بين 1.07 و1.11. كما أظهرت التصاميم نطاقًا ترددیًا واسعًا يبلغ 80 جيجا هيرتز، وحققت ربحًا محققًا مرتفعًا ضمن النطاق 7.01–7.28 dBi، وهو ما يُعد قابلًا للمقارنة مع القيم المبلغ عنها في دراسات سابقة لهوائيات التيراهرتز. وتشير هذه النتائج إلى أن ® ZEONEX يمثل مادة ركيزة واعدة لتصميم هوائيات التيراهرتز في أنظمة الاتصالات من الجيل القادم.

1. Introduction

The rapid growth of data-intensive applications, including high-definition video streaming, real-time online events, and live broadcasting, has significantly increased the demand on wireless data networks. Wireless data traffic analysis predicts that the mobile-connected device population will grow exponentially to over 18.22 billion by 2025 [1].

As the demand for better data rates and ultra-high-speed communication increases, there is a push for new technologies, such as the sixth generation (6G) system, expected to emerge by 2030 [2].

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While fifth-generation (5G) networks reach a maximum speed of 20 Gbps, 6G networks will push the limits even further, achieving a higher speed of 1 Tbps [1, 3, 4].
The 6G wireless communication system will significantly rely on the terahertz (THz) spectrum band [2, 5]. THz waves, which are known as submillimetre radiation, represent the frequency range between 0.1 and 10 THz, with corresponding wavelengths between 3 millimetres (mm) and 0.03 mm [5]. The THz band is located between the microwave region and the infrared region in the electromagnetic spectrum [2, 6]. The frequency ranges from 0.1–0.3 THz refers to the sub-THz region, while the range from 0.3–10 THz refers to the THz region [2]. The THz band in the electromagnetic spectrum is also known as T-waves or Tera waves [2].
Various industries can benefit from the incorporation of wireless communication throughout the terahertz (THz) band. Applications are diverse and promising, including high-speed THz cellular networking, Tbps Tera-WiFi, Internet of Nano-Things (IoNT), Tbps integrated access backhaul (Tera-IAB) networks, THz wireless personal area networks (T-WPANs), and on-chip communications [1, 2].
Antennas play a crucial role in terahertz (THz) communication since next-generation wireless systems will need high-speed data transmission. Various kinds of antennas have been proposed for terahertz spectrum applications, which include the microstrip patch antenna, leaky-wave antenna, Yagi-Uda antenna, bow-tie antenna, monopole antenna, and log-periodic antenna [6, 7].
Microstrip patch antennas provide several advantages over other antenna types, making them a suitable antenna choice for modern communication technologies, including 6G applications. They are characterized by their simple structure, low profile, easy to feed, inexpensive manufacturing process, compatibility with Monolithic Microwave Integrated Circuit (MMIC) [8], capability to function at short wavelengths, reconfigurability, and dependability [9]. The design process of a patch antenna is primarily affected by three factors, which include return loss (the impedance matching between the antenna and its port), dielectric loss (the type of material used for the substrate layer), and conductor loss (affected by the conductivity of the selected patch material) [9].
Researchers and antenna engineers have utilized various materials in the design of THz antennas for THz communication systems, making material selection a critical and highly challenging endeavor. Selecting an appropriate patch material is challenging because material properties influence antenna performance at THz frequencies. Jayanth et al. [10] proposed a single-element antenna design at a high frequency of 250 GHz. The introduced structure used copper material for both the ground layer and the radiating element, while a polyimide film with a dielectric constant (ε_r) = 3.4 was used as the substrate material. The simulation results of the simulated antenna provided a gain of 6.41 dBi and a −10 dB bandwidth of 8.25 GHz, between 246.50 GHz and 254.75 GHz, indicating its suitability for 6G applications.
Saeed et al. [11] proposed a compact U-shaped terahertz microstrip patch antenna operating at 0.85 THz for a 6G system. The designed structure used copper as a radiating element, and Rogers RO3010 was used as a substrate with a dielectric constant value of 11.2. Their design provided a return loss value of −19.5 dB and a bandwidth value of 44 GHz. However, their design used a high-permittivity material. In contrast, this work concentrates on the higher 3 THz band and utilizes the low-loss polymer ZEONEX® substrate with different conducting materials.
Biradar et al. [12] presented a design and simulation for a multi-slot triangular microstrip patch antenna using copper as the patch and FR-4 as the substrate at an operating frequency of 3.16 THz. The performance parameters, such as return loss, voltage standing wave ratio (VSWR), bandwidth, and gain, were simulated using the Computer Simulation Technology (CST) tool; the simulation results indicated the suitability of the proposed design for the upcoming 6G communication system.
Similar to the selection of radiating patch materials, choosing a dielectric substrate material is also important for patch antenna performance, as its dielectric constant and substrate thickness strongly impact antenna design and performance parameters. Recent research is being conducted on different substrates such as polyimide [10], silicon dioxide, quartz, silicon, and silicon nitrate [13]. However, they did not consider some other substrate materials for terahertz applications, such as ZEONEX®.
While several studies focus on using conductive materials like copper for THz antenna design, there is a lack of research on low-loss polymeric substrates, specifically ZEONEX®, in the THz region. Additionally, there is a significant gap in systematic comparative studies on the performance of various conductors, such as aluminum, copper, gold, and silver, used on ZEONEX® substrates at 3 THz. This gap limits a comprehensive understanding of the best material combinations to improve patch antenna performance for emerging 6G communication systems. In this work, inset-feed microstrip patch antennas with four different conductive materials (aluminum, copper, gold, and silver) on a ZEONEX® substrate are analyzed and compared at 3 THz.
The manuscript is organized as follows: The geometry and configuration of the proposed antennas are presented in Section 2. In Section 3, the substrate material properties of ZEONEX® are discussed. Material properties of aluminum, copper, gold, and silver as radiating element patches are discussed in Section 4. Section 5 introduces simulation results, discussion, analysis, and comparison, and Section 6 concludes the manuscript.

2. GEOMETRY AND CONFIGURATION OF PROPOSED ANTENNA

The introduced 3 THz inset-fed patch antenna has been designed and simulated using CST Studio 2022. The proposed structure consists of a radiating patch, a copper ground plane, and a Zeonex substrate characterized by its low dielectric constant (2.31) and 3-µm thickness. Four different conductive materials, aluminum, copper, gold, and silver, were individually employed for the radiating patch to evaluate their impact on antenna performance with a Zeonex substrate. In this work, copper was deliberately kept as the ground-plane material to provide a controlled comparative analysis. If both the radiating patch and ground-plane materials were varied concurrently, it would be difficult to attribute the observed differences in antenna performance solely to the patch material. Consequently, only the patch conductor was altered, while the ground plane remained fixed across all simulation cases. This strategy isolates the contribution of the radiating patch conductor and ensures a consistent comparison under identical simulation conditions. It should be emphasized that this is a methodological choice adopted for comparative investigation and does not imply that copper is the universally optimal material for the ground plane. A microstrip antenna design is developed through several phases. The design process includes the following steps:

- Identify the operational frequency.
- Choose an appropriate substrate.
- Establish the height of the substrate.
- Determine the antenna's dimensions.

Fig. 1 indicates the flowchart of the proposed antenna production and analysis.

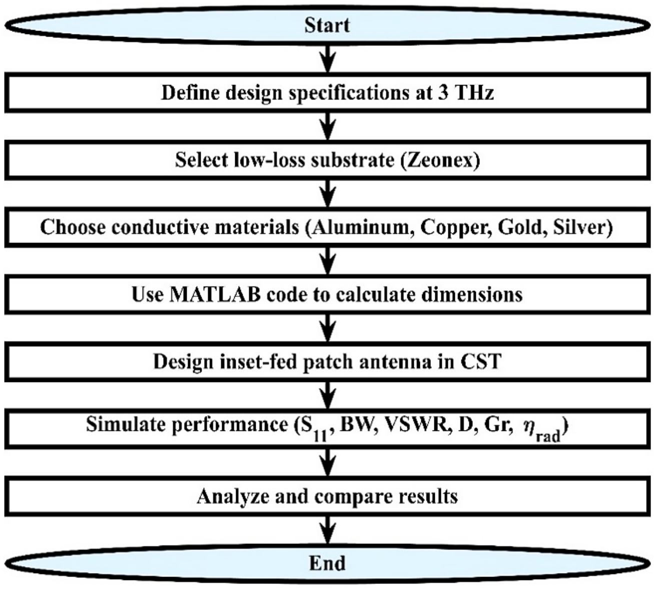


Fig. 1: Flowchart of the proposed antenna design methodology.

The design equations used in Matlab code to calculate antenna dimensions are introduced below.
At first, the substrate thickness h was determined based on the following relationship [14]:

$$h \leq \frac{0.3c}{2\pi f_r \sqrt{\varepsilon_r}} \tag{1}$$

Where f_r is the resonant frequency = 3 THz, and c is the speed of light =3 $\times 10^8$ m/s. Considering the above formula, Zeonex was chosen as the substrate with a thickness of h =3μm, permittivity $\varepsilon_r = 2.31$, and tanδ =0.0003. The width of the patch W_p is calculated by [14]:

$$W_p = \frac{c}{2f_r}\sqrt{\frac{2}{\varepsilon_r + 1}} \tag{2}$$

In order to find the length of the radiating patch, it is essential first to calculate the effective permittivity ε_{reff} of the substrate. This is defined by the following equation [14]:

$$\varepsilon_{reff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2\sqrt{1 + 12\frac{h}{W_p}}} \tag{3}$$

After computing ε_{reff}, the following relationship should be used to calculate the patch effective length L_e [14]:

$$L_e = \frac{c}{2f_r\sqrt{\varepsilon_{reff}}} \tag{4}$$

Next, we use the following relationship to determine how much the patch should be shortened [14]:

$$\Delta L = \frac{0.412 \cdot h(\varepsilon_{reff} + 0.3)\left(\frac{W_p}{h} + 0.264\right)}{(\varepsilon_{reff} - 0.258)\left(\frac{W_p}{h} + 0.8\right)} \tag{5}$$

Then, the value of the patch length is calculated as follows [14]:

$$L_p = L_e - 2\Delta L \tag{6}$$

Once the dimension of the radiating element is determined, the substrate and ground plane dimensions (L_s, L_g, W_s, W_g) must be calculated. In this study, the substrate and ground plane dimensions are considered equal. The following equations are used to compute them [14]:

$$L_s = L_g = L_p + 6h \tag{7}$$

$$W_s = W_g = W_p + 6h \tag{8}$$

The width of the feed line W_f is calculated from the following equation in order to obtain a 50 Ω characteristic impedance [15]:

$$W_f = h\left(\frac{377}{50\sqrt{\varepsilon_r}} - 2\right) \tag{9}$$

The inset feed Depth F_i is determined using the following equation [16]:

$$F_i = 10^{-4}[0.001699\varepsilon_r^7 + 0.13761\varepsilon_r^6 - 6.1783\varepsilon_r^5 + 93.187\varepsilon_r^4 - 682.69\varepsilon_r^3 + 2561.9\varepsilon_r^2 - 4043\varepsilon_r + 6697](Lp/2) \tag{10}$$

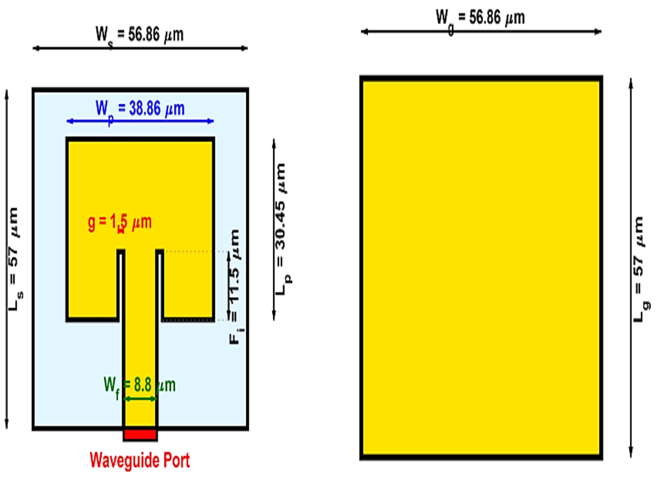
The feed line length (L_f) is determined from the following equation [14]:

$$L_f = 3 \times h \tag{11}$$

Table 1 provides the proposed Zeonex®-based substrate patch antenna design parameters, which are uniformly applied to all four conductive patch elements at 3 THz operating frequency.

Table 1: Design Parameters

Antenna Parameter	Symbol	Dimensions (μm)
Ground plane width	W_g	56.86
Ground plane length	L_g	57
Substrate plane width	W_s	56.86
Substrate plane length	L_s	57
Patch width	W_p	38.86
Patch length	L_p	30.45
Patch thickness	P_{thick}	0.3
Ground thickness	G_{thick}	0.3
Substrate thickness	h	3
Feed line width	W_f	8.8
Feed line length	L_f	13.359
Inset feed Depth	F_i	11.5
Notch gap	g	1.5



(a) (b)

Fig. 2: Proposed Antenna model view: (a) front view; (b) back view.

The proposed model antenna view from the front and back sides is shown in Fig. 2(a) and Fig. 2(b), respectively.

3. ZEONEX®

Cyclic olefin polymer (Zeonex®, trade name) is a polymer material [17] that has attracted attention due to its outstanding optical transparency, high-precision moldability, and low moisture absorption [18]. ZEONEX® is useful for a variety of purposes. It can be utilized for medical applications due to its high-purity property advantage. Furthermore, it can be applied to dielectric materials due to its low dielectric constant and low dielectric loss tangent [18]. ZEONEX® has a dielectric permittivity of 2.31 over a terahertz frequency band from 0.1 to 4.5 THz [19]. Its dielectric loss tangent is 0.0003 [20]. At higher THz frequencies, ZEONEX has been reported to exhibit lower material losses than several commonly used polymer materials, such as PTFE (Teflon) and HDPE [21]. The main physical, optical, thermal, electrical, and mechanical characteristics of the ZEONEX® polymer material, have been reported in the literature [19, 20, 22]. Several dielectric materials, including Rogers RO3010, quartz, and PTFE (Teflon), have been explored for THz microstrip antenna applications because the substrate plays a critical role in determining the antenna dimensions and overall electromagnetic performance. The target resonant frequency, substrate thickness, and relative permittivity govern the effective and physical patch dimensions. Generally, using a substrate with a higher relative permittivity reduces the antenna's physical dimensions; however, this reduction is often associated with degraded antenna performance [23].
In addition to the dielectric constant, the dielectric loss tangent (tanδ) is another key factor affecting the performance of microstrip antennas. Previous investigations have indicated that the loss tangent has a considerable influence on antenna performance and gain, as the substrate loss tangent increases, the antenna gain decreases, whereas the antenna bandwidth tends to increase; overall, higher values of the substrate loss tangent can degrade the performance of microstrip patch antennas [24]. Therefore, dielectric materials with a low loss tangent can be preferred for high-frequency microstrip antenna applications, particularly within the terahertz band.
Comparative material studies presented in the literature further indicate that conventional dielectric substrates exhibit different trade-offs between dielectric constant and dielectric loss. For instance, polyimide commonly possesses a dielectric constant of approximately 3.5 [23] and a loss tangent of about 0.0027 [1], whereas quartz has a dielectric constant of approximately 3.75 [23] and a loss tangent close to 0.0002 [1]. PTFE (Teflon) possesses a relatively low dielectric constant of 2.10 [23] and a very low loss tangent of 0.0002 [1]. Cyclic olefin-based polymers, including TOPAS (COC) and ZEONEX (COP), exhibit lower dielectric constants of 2.30 and 2.31, respectively [19], together with highly comparable low dielectric-loss characteristics (tanδ≈0.0003) [20]. These properties make them promising polymer-based dielectric materials for THz electromagnetic devices
Previous studies have indicated that polymer-based materials commonly demonstrate lower terahertz absorption than conventional

glass-based materials, making them attractive candidates for low-loss THz electromagnetic applications [21]. Within this class of polymers, ZEONEX (cyclo-olefin polymer, COP) and TOPAS (cyclic olefin copolymer, COC) have been reported as promising polymeric substrate materials because of their comparably low absorption coefficients across the terahertz band [21]. Moreover, at higher THz frequencies, both ZEONEX and TOPAS exhibit lower material losses than PTFE (Teflon) and HDPE, further supporting their suitability for high-frequency terahertz devices [21]. Overall, these studies indicate that ZEONEX and TOPAS are among the most promising low-loss polymeric substrate materials for THz electromagnetic applications [21].

Although both ZEONEX and TOPAS exhibit favorable dielectric properties for THz applications, ZEONEX® was employed in this work not because it is universally superior to TOPAS, but rather because it provides a well-characterized, low-dielectric-loss substrate platform that enables the influence of different patch conductor materials to be investigated under identical conditions. It is important to emphasize that the novelty of this study does not arise from introducing ZEONEX as a novel substrate material, since its advantageous dielectric properties have already been well established in the literature. Instead, ZEONEX® was intentionally selected as a low-loss reference substrate to isolate the effect of different patch conductor materials while maintaining identical antenna geometry, substrate thickness, operating frequency, and feeding conditions. Consequently, the primary scientific contribution of this work is the systematic comparative evaluation of four patch conductor materials copper, aluminum, silver, and gold in a THz microstrip antenna. This approach enables the individual contribution of the conductor material to be quantitatively assessed without confounding effects arising from substrate-related variations. To the best of the authors' knowledge, the available literature does not report a systematic comparative investigation of these four patch conductor materials using an identical ZEONEX-based THz microstrip antenna configuration under the same antenna geometry, substrate thickness, operating frequency, and feeding conditions.

4. Zeonex® based substrate patch antenna with different materials

Dimensions of all four antenna designs are identical. In this research, ZEONEX® is used as the substrate material in all antenna configurations, while the radiating patch is realized using four different conductor materials: aluminum, copper, silver, and gold. To ensure realistic electromagnetic modeling, both the radiating patch and the ground plane were modeled as finite-conductivity (lossy metal) materials rather than perfect electric conductors (PEC). Therefore, the finite electrical conductivity and the associated conductor losses of each metal were taken into account during the CST simulations. The material properties, advantages, and limitations of aluminum, copper, gold, and silver as radiating patch materials are discussed in this section

a. Zeonex® based substrate aluminum patch antenna

In this structure, aluminum serves as the patch element and copper as the ground bottom layer, with a Zeonex® substrate sandwiched between the patch and ground layers. Aluminum is widely used for its high conductivity and is one of the most abundant nonferrous metals in the Earth's crust [25]. It is infinitely recyclable, making recycling more efficient than producing primary aluminum and helping protect the environment. Additionally, aluminum has much lower pollution levels than copper, contributing to a more environmentally friendly structure [26]. Due to its notable advantages of being lightweight and environmentally sustainable because of its high recyclability, aluminum is an attractive candidate for THz applications. The properties of aluminum are presented in [27-30].

b. Zeonex® based substrate Copper patch antenna

In this antenna structure, copper is used as a patch on the top and as a ground on the bottom; a Zeonex® substrate is sandwiched between the top and bottom layers. Copper is known for its excellent electrical conductivity and is the most widely used material in RF and microwave electronic applications. Due to its superior electrical and physical properties, it is the most common material for 5G and 6G antenna design [12]. The properties of copper have been widely reported in the literature [30-32].

c. Zeonex®-based substrate gold patch antenna

In this antenna design, gold is used as a patch on the top, and copper serves as the ground at the bottom; a Zeonex® substrate is sandwiched between the top and bottom sides. Gold is chosen for microwave devices because of its simple processing and high conductivity; these reasons are due to gold's chemical inertness in ambient conditions [9]. Since it does not change its properties at higher terahertz frequencies, it is the preferred material for terahertz antennas. Gold is selected as the radiating material because it is chemically stable and resistant to corrosion. Although the skin depth of gold is smaller (about 75 nm at 1 THz), it still shows significant electrical conductivity at THz frequencies [9]. The main properties of gold material have been reported in [9].

d. Zeonex® based substrate silver patch antenna

This design uses silver as a patch element and copper for the ground layer. Zeonex® substrate is sandwiched between them. Silver is frequently used in terahertz (THz) antenna design because of its outstanding electrical conductivity. The use of highly conductive materials, such as silver, improves performance metrics of antennas, such as gain, bandwidth, and overall efficiency. Additionally, integrating silver into metamaterial-based ground structures helps reduce back radiation, thereby enhancing the antenna's radiation efficiency [9]. The properties of silver material have been reported in [9].

5. Discussion, Analysis, and Comparison of Simulation Results

In this section, four proposed antenna structures were designed and simulated using the Computer Simulation Technology (CST) Studio Suite 2022 [30] at an operating frequency of 3 THz. The operating frequency of 3 THz was selected because it lies within the 0.1–10 THz band, which has been widely recognized as a promising portion of the electromagnetic spectrum for future 6G communication systems [1,2]. In addition, ZEONEX® 480R has been experimentally characterized using terahertz time-domain spectroscopy (THz-TDS) over a frequency range extending from approximately 0.1 to 4.5 THz [19]. Therefore, the selected operating frequency of 3 THz lies well within the experimentally characterized frequency range of the substrate material. This work aims to evaluate the influence of different conductive patch materials on antenna performance at the selected THz operating frequency rather than to compare antenna performance across multiple operating frequencies. Consequently, the selection of 3 THz was intended to establish a well-characterized operating point for the comparative analysis, rather than to claim that it is universally optimal for all THz applications. Mesh convergence was verified using the adaptive tetrahedral mesh refinement procedure in CST Studio Suite. The frequency-domain solver automatically refined the mesh through successive adaptive refinement passes until the predefined convergence criterion was achieved. The same solver settings and mesh refinement procedure were applied to all investigated antenna structures to ensure a consistent comparison. The simulated performance is evaluated in terms of Return loss (S_{11}), Bandwidth (BW), Voltage Standing Wave Ratio (VSWR), Directivity (D), Realized gain (G_r), and Radiation efficiency (ηrad).

a. Return Loss and Bandwidth

Return loss (measured in decibels, dB) refers to the difference between the incident power on the antenna and the reflected power from it [13]. It shows how the antenna is effectively matched with the transmission line. -10 dB return loss represents the reference value, which means that 90% of the incident power is received by the antenna, and the remainder is reflected to the antenna. This figure is considered acceptable in mobile communication [14]. In Fig. 3, the return loss of the proposed 3 THz Zeonex-based substrate patch antenna for different patch materials, aluminum (Black line), copper (red line), gold (green line), and silver (blue line) are plotted.

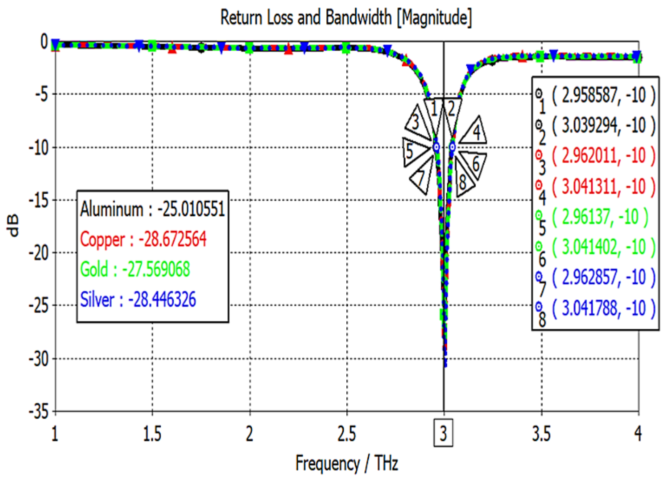


Fig. 3: Return loss and Bandwidth of different patch materials at 3 THz.

Here, it can be observed aluminum provides a return loss of -25.01 dB at a resonant frequency of 3.00 THz, copper gives a return loss of - 28.67 dB at a resonant frequency of 3.00 THz, gold provides a return loss of – 27.56 dB at a resonant frequency of 3.00 THz, and silver provides a return loss of – 28.44 dB at a resonant frequency of 3.00 THz, all four conductive materials designs exhibit good impedance matching around 3 THz, as indicated by the return loss values below −20 dB. In terms of bandwidth, it is defined as the frequency range in which the return loss is below -10 dB [16]. In Fig. 3, it can be observed that the proposed designs achieve a wide operational bandwidth of approximately 80 GHZ, which demonstrates sufficient spectral capacity to support the next 6G applications.

b. Voltage standing wave ratio

The voltage standing wave ratio (VSWR) is one of the antenna performance parameters that indicates how effectively power is delivered to the load from a power source through a transmission line [13]. The ideal value of VSWR is equal to 1, and a value less than 2 is considered an acceptable value for most antenna applications [14]. Fig. 4 provides VSWR plots of the proposed structures at 3 THz frequency for aluminum, copper, gold, and silver patch materials. The results plot of VSWR is found to be within the suitable range (< 2), indicating good impedance matching. Copper shows the lowest VSWR value of 1.076, followed by silver (1.079), gold (1.087), and aluminum (1.118). Overall, all materials demonstrate satisfactory results suitable for THz antenna applications.

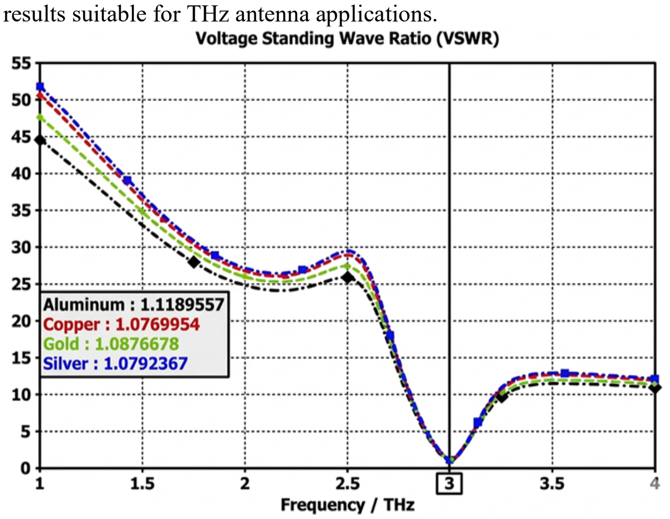


Fig. 4: VSWR of different patch materials at 3 THz.

c. Directivity

Directivity (D) is one of the significant antenna performance parameters that evaluates the antenna power density in the direction of its maximum radiation [13]. The proposed Zeonex® based substrate antenna with different patch materials shows high directivity values at 3THz, as shown in Fig. 5, with aluminum patch material having the highest gain of 9.12 dBi, copper patch material 9.10 dBi, followed by silver patch with 9.097 dBi, and the lowest value is for gold patch with 9.095 dBi as directivity.

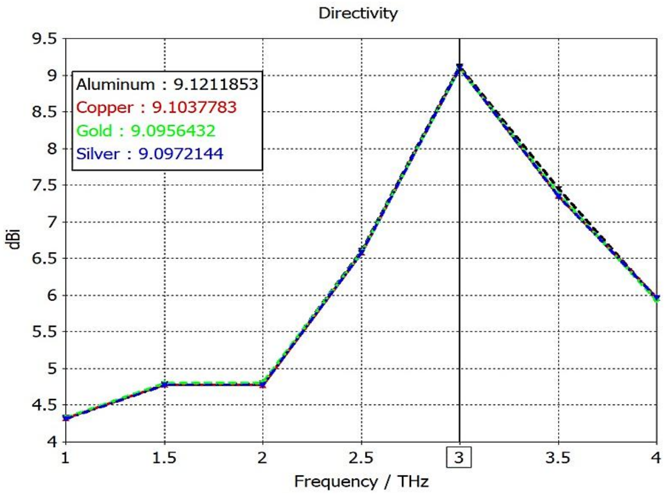


Fig. 5: Directivity of different patch materials at 3 THz.

d. Realized Gain

In general, antenna gain is defined as the ratio of the antenna power density at a specific point to the power density of an isotropic antenna at the same point when the same amount of power is applied to both [16]. While some efficiency loss and mismatching loss are not included in the gain, they are included in the realized gain; as a result, the realized gain (G_r) is less than the gain [16]. Fig. 6 shows the realized gain plots for the proposed structures at a frequency of 3 THz. The proposed antenna designs achieve a gain between 7.01 and 7.31 dBi at a resonance frequency of 3 THz, which is considered high for a compact patch design.

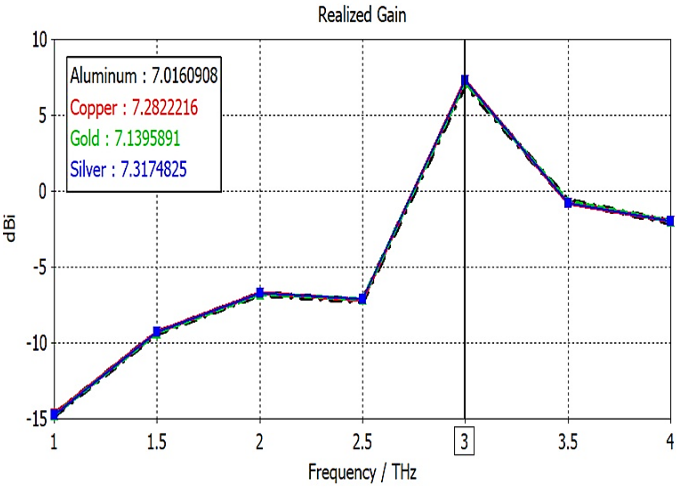


Fig. 6: Realized gain of different patch materials at 3 THz.

e. Radiation efficiency

It is defined as the ratio of the total power radiated by the antenna design and the total input power inserted into the same design [16]. This performance parameter evaluates how well the antenna design is effective in the process of radiating and receiving electromagnetic waves; therefore, it should be higher for better performance [16].

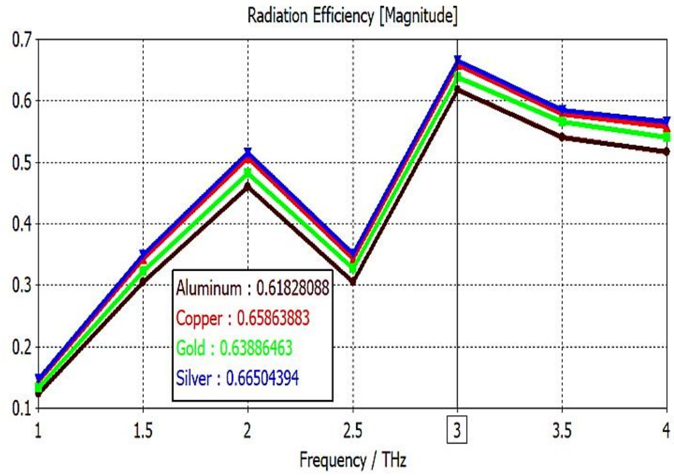


Fig. 7: Radiation efficiency of different patch materials at 3 THz.

Fig. 7 indicates the radiation efficiency plots for the proposed structures at a frequency of 3 THz. The results show a direct and linear relationship between the conductivity of the material and the resulting efficiency: Silver (66%) is the most efficient, followed by copper (65%), Gold (63%), and Aluminum (61%). Both conductor and dielectric losses affect radiation efficiency in the THz band. Conductor losses increase due to the skin effect, which causes current to concentrate near the conductor surface and increases the effective resistance of metallic conductors, while dielectric losses result from electromagnetic energy dissipation within the dielectric substrate, particularly in materials with higher loss tangent values [33]. However, in the present work, the same ZEONEX dielectric substrate and the same ground plane were employed for all proposed antenna structures; therefore, the dielectric loss remained essentially constant. Accordingly, the observed variation in radiation efficiency is primarily attributed to differences in the electrical conductivity of the patch materials. While conductor losses account for the variation in radiation efficiency among the investigated materials, the overall radiation efficiency remains below 100% because of the combined effect of conductor and dielectric losses at THz frequencies.

Overall, the observed differences among the investigated patch materials are consistent with their electrical properties. Since all antenna configurations share the same geometry, ZEONEX substrate, and ground plane, only minor variations are observed in the impedance characteristics (S_{11} and VSWR) and directivity. In contrast, the realized gain and radiation efficiency are more sensitive to the electrical conductivity of the patch material. Consequently, silver and copper exhibit slightly higher realized gain and radiation efficiency than gold and aluminum due to their lower conductor losses associated with their higher electrical conductivity [33].

The proposed THz microstrip patch antenna is intended to serve as the radiating element of a future 6G RF transceiver. According to [34], a typical 6G RF transceiver comprises RF front-end components such as amplifiers, mixers, phase shifters, and antennas, where the antenna functions as the element responsible for transmitting and receiving electromagnetic waves within the overall communication system. Accordingly, the proposed antenna may be integrated into such a transceiver architecture, whereas the design and implementation of the complete RF transceiver remain outside the scope of the current work.

Although the proposed antenna demonstrates satisfactory simulated performance at 3 THz, practical THz communication systems face propagation challenges beyond the antenna design itself. According to [1], THz wave propagation is significantly affected by atmospheric attenuation, primarily due to water vapor absorption, while free-space path loss becomes dominant at frequencies above 300 GHz. Consequently, high-gain antenna arrays and beamforming techniques are commonly employed to compensate for these propagation losses [1]. These propagation challenges are related to the wireless propagation environment rather than the antenna design and are therefore beyond the scope of the present work.

The skin depth at 3 THz is calculated using the following expression [35]

$$\delta = \sqrt{\frac{1}{\pi f \mu \sigma}} \qquad (12)$$

Where f is the operating frequency, μ magnetic permeability of conductor ($\mu = \mu_0\ \mu_r$), $\mu_0 = 4\pi \times 10^{-7}$ H/m represents the permeability of free space, μ_r is the relative permeability, and σ is the electrical conductivity of the conductor. Using the electrical conductivities of the investigated metals at 3 THz, the calculated skin depths are approximately 36.6 nm for silver, 38.2 nm for copper, 43.0 nm for gold, and 49.1 nm for aluminum. Since the adopted patch thickness is 0.3 μm (300 nm), it is approximately 6–8 times greater than the corresponding skin depth for all investigated metals. Therefore, the selected patch thickness is sufficient to support the induced surface current and is not expected to limit the antenna performance. Therefore, the selected patch thickness is sufficient to support the induced surface current and is not expected to limit the antenna performance.

A detailed investigation of surface plasmon polariton (SPP) effects is beyond the scope of the present study. The present work focuses on the comparative performance of a conventional metallic microstrip patch antenna using different patch materials.

f. Comparison of the Proposed Antenna Designs with Other Designs

The obtained antenna performance results for the proposed microstrip patch antennas can be compared with other published design results in terms of S_{11}, VSWR, realized gain, Directivity, and Efficiency for comparative evaluation. Table 2 presents a comparative summary of proposed designs similar to structures described in [10, 11,13]. The proposed Zeonex®-based patch antenna structure (Pro. Dsg 1–4) indicates notable performance improvements in comparison to previously published research [10,11,13] across performance parameters, including return loss, bandwidth, and gain. Previously published antenna designs utilizing polyimide [10], Roger RO3010 [11], quartz, and silicon [13] as substrates, and operate in the sub-terahertz frequency band (250–854 GHz), whereas the proposed structures provide stable resonance at 3 THz, indicating superior scalability for terahertz frequency band applications. The Zeonex® based substrate patch antenna, characterized by its low dielectric loss tangent and consistent permittivity, offers good impedance matching with VSWR values extended from 1.07 to 1.11, in contrast to higher values reported for conventional materials (up to 3.0 for quartz and silicon). Correspondingly, the proposed designs achieve improved return loss levels between –25.01 dB and –28.65 dB, outperforming reference antennas, which exhibit return losses from –11.42 dB to –26.22 dB, thus confirming enhanced impedance stability and reduced signal reflection. Furthermore, the introduced structures exhibit a wide impedance bandwidth of 80 GHz, surpassing that of previous research such as the polyimide-based [10] (8.25 GHz), Roger RO3010 [11] (44 GHz), and quartz-based [13] (8.4 GHz) designs. In addition, the proposed designs enable high radiation gain in the range of 7.01–7.28 dBi, whereas the reference comparable studies provide lower values (1.32–6.42 dBi). These results collectively indicate that Zeonex® is a promising substrate material for THz antenna design, enabling an advantageous low return loss, high gain, wide bandwidth, and good impedance matching. As a result, the proposed designs provide a compact and high-performance antenna solution appropriate for upcoming terahertz communication systems and applications.

6. Conclusion

In this research, microstrip patch antennas operating at 3 THz were investigated using ZEONEX® as the common substrate and a fixed copper ground plane, while four different conducting materials were evaluated for the radiating patch. The results indicate that the proposed designs provide good performance compared with previously reported studies, achieving good matching (VSWR ≤ 1.11), a wide bandwidth of 80 GHz, and high realized gain (7.01–7.28 dBi). These results demonstrate the potential of the low-loss ZEONEX® substrate for THz antenna applications and indicate its suitability for compact and high-performance patch antennas for future THz 6G communication systems. It should be noted that this work focuses on numerical design and electromagnetic simulation. The selected substrate thickness was determined according to established microstrip antenna design criteria for the target operating frequency. Experimental fabrication and validation are beyond the scope of the present study and are left for future experimental studies.

Table 2: Comparison of the Proposed Antenna Designs with Other Designs

Reference No.	Substrate material	Size	fr	S_{11}(dB)	BW(GHZ)	VSWR	Gain
[10]	polymid	0.48×0.54mm^2	250GHz	-11.421	8.25	1.162	6.42 dB
[11]	Roger RO3010	200×200 μm^2	0.854THz	-19.5	44	-	3.88dBi
[13]	Quartz	-	301GHz	-15.18	8.4	3	4.10
[13]	Silicon	-	299.91GHz	-20.62	1.49	1.6	1.32
[13]	Silicon	400×400 μm^2	300.34GHz	-26.22	1.47	0.8	-
[13]	Silicon	400×400 μm^2	300.58GHz	-20.03	1.48	1.7	-
Pro. Dsg.1	Zeonex®	57×56.86 μm^2	3THz	-25.01	80	1.11	7.01dBi(Gr)
Pro. Dsg.2	Zeonex®	57×56.86 μm^2	3THz	- 28.65	80	1.07	7.28dBi(Gr)
Pro. Dsg.3	Zeonex®	57×56.86 μm^2	3THz	– 27.55	80	1.08	7.14dBi(Gr)
Pro. Dsg.4	Zeonex®	57×56.86 μm^2	3THz	– 28.41	80	1.07	7.14dBi(Gr)

7. AI Use Statement

ChatGPT (OpenAI) was primarily used to assist with language editing, improving the clarity and presentation of the manuscript, and preparing responses to reviewers. Undermind was used to a limited extent for language refinement and text rephrasing. Paperpal was used to assist with translating the abstract into Arabic. All scientific content, analyses, interpretations, revisions, and final decisions were reviewed and approved by the author, who takes full responsibility for the manuscript.

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