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Design and Wideband Performance Analysis of a 40-GHz Bicone Antenna for Millimeter-Wave Radar Applications

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تصميم وتحليل أداء هوائي واسع النطاق Bicone بتردد 40 جيجاهرتز لتطبيقات الرادار بالموجات المليمترية

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Abstract:
This work describes the design and simulation of a compact Bicone antenna optimized for 40-GHz millimeter-wave (mmWave) radar. The antenna employs the broad bandwidth feature of biconical structures to ensure stable impedance matching at high frequencies. ANSYS HFSS full-wave electromagnetic modeling is used to optimize cone angles, feed design, and overall size. Results demonstrate excellent return-loss performance near 40 GHz, with a wide bandwidth that enables reliable radar sensing in various conditions. The radiation pattern remains stable and nearly omnidirectional, making it ideal for short-range detection. Simulated gain confirms its suitability for high-precision mmWave radar systems. The structure's low profile and simple mechanics facilitate fabrication and integration. Performance comparisons highlight its advantages over traditional narrowband antennas. Overall, the proposed bicone antenna exhibits strong potential for future 40-GHz radar applications.

Keywords: Bicone antenna, Wideband antennas, Next-generation radar systems, mmWave, radiation pattern.

الملخص
يقدّم هذا العمل تصميمًا ومحاكاة لهوائي ثنائي المخروط (Bicone) مدمج مُحسَّن للعمل عند تردد 40 جيجاهرتز لتطبيقات الرادار ذات الموجات المليمترية (mmWave). يتميز هذا الهوائي بخاصية النطاق العريض المتأصلة في الهياكل ثنائية المخروط لتحقيق توافق ممانعة مستقر عند الترددات العالية. تم إجراء نمذجة كهرومغناطيسية كاملة الموجة باستخدام برنامج **ANSYS HFSS** لتحسين زاوية المخروط، وتصميم التغذية، والأبعاد الكلية للهوائي. تُظهر نتائج المحاكاة أداءً ممتازًا لفقدان الانعكاس بالقرب من 40 جيجاهرتز، إلى جانب نطاق ترددي واسع يتيح استشعارًا موثوقًا للرادار في ظروف تشغيل مختلفة. يحافظ نمط الإشعاع على استقراره ويكون شبه شامل الاتجاه، مما يجعل الهوائي مناسبًا لتطبيقات الكشف قصير المدى. كما تؤكد قيمة الكسب المحاكى ملاءمته لأنظمة الرادار عالية الدقة ذات الموجات المليمترية. يسهّل الشكل منخفض الارتفاع والبنية الميكانيكية البسيطة عملية التصنيع والتكامل مع الأنظمة المختلفة. وتبرز مقارنات الأداء تفوّق هذا الهوائي على الهوائيات التقليدية ذات النطاق الضيق. وبشكل عام، يُظهر الهوائي ثنائي المخروط المقترح إمكانات قوية لتطبيقات الرادار المستقبلية عند تردد 40 جيجاهرتز.

الكلمات المفتاحية: هوائي مخروط، هوائيات عريضة النطاق، رادار الجيل القادم، mmWave، نمط الاشعاع.

Introduction

Millimeter-wave radar systems have become essential in modern sensing technologies due to their capability to provide high resolution, rapid response, and robust target detection [1], [2]. Operating at 40 GHz offers an attractive balance between compact antenna size and adequate penetration for short-range radar applications [3], [4].

With increasing demand in automotive sensing, industrial monitoring, and security screening, antenna performance at mmWave frequencies has become a critical research focus [5]. However, antenna design at these frequencies presents challenges related to fabrication tolerances, material losses, and maintaining a wide impedance bandwidth [6].

The Bicone antenna stands out as a promising candidate thanks to its inherently broadband characteristics and rotationally symmetric radiation behavior. Its smooth geometric transition supports stable impedance over a wide frequency range, reducing reflections and improving matching [7]. These features make it suitable for radar systems that require reliable performance across varying operational conditions [8].

At 40 GHz, the bicone's compact size also enables easy integration into portable or embedded platforms [9]. Additionally, the antenna's omnidirectional pattern enables consistent target illumination in short-range detection scenarios. Advances in simulation tools now allow precise optimization of the bicone geometry for mmWave applications. Full-wave modeling enables accurate prediction of return loss, gain, and field distribution.

This study used a comprehensive approach combining theoretical antenna design principles with full-wave electromagnetic simulation tool ANSYS HFSS to optimize a 40 GHz bicone antenna. The initial geometry was based on classical biconical theory to achieve a natural impedance close to 50 Ω. Variations in cone angle, height, and feed gap were examined to improve impedance matching and increase bandwidth. The design was validated through electromagnetic modeling, accurately predicting return loss, VSWR, gain, radiation patterns, and group delay. This integrated method ensured alignment between theoretical predictions and simulated performance, confirming the antenna's effectiveness for next-generation radar systems.

1. Literature Review

Millimeter-wave (mmWave) radar systems have gained significant attention due to their ability to provide high spatial resolution, fast response, and reliable target detection, making them suitable for automotive, industrial, and security applications. Operating frequencies around 40 GHz offer a practical compromise between antenna compactness and propagation capability for short-range radar systems

Several studies highlight that antenna design at mmWave frequencies faces critical challenges, including fabrication tolerances, conductor and dielectric losses, and maintaining wide impedance bandwidth. These issues become more severe as frequency increases, often limiting the performance of conventional narrowband antennas

Biconical antennas have long been recognized for their inherently broadband impedance characteristics and rotational symmetry. Classical antenna theory confirms that the smooth geometric transition of biconical structures enables stable impedance matching over wide frequency ranges without requiring additional matching networks. This makes them attractive candidates for broadband radar and sensing systems

Recent research has explored the application of bicone and wideband antennas at millimeter-wave frequencies, demonstrating their suitability for broadband operation and omnidirectional radiation. Compared to planar and compact mmWave antennas, biconical designs generally provide wider bandwidth but moderate gain, which is acceptable for short-range radar applications requiring uniform angular coverage rather than high directivity

Survey studies on mmWave antennas further emphasize that while arrays and directional antennas can achieve higher gain, they often introduce increased complexity, narrow bandwidth, and higher fabrication costs. As a result, there is growing interest in simple, wideband antenna structures such as biconical antennas that balance performance, bandwidth, and ease of integration

2. Methodology

The methodology adopted in this work combines classical antenna theory with full-wave electromagnetic simulation to design and optimize a compact bicone antenna operating at 40 GHz for millimeter-wave radar applications. The overall design process consists of theoretical parameter estimation, geometric modeling, numerical optimization, and performance evaluation using ANSYS HFSS

The cone height was chosen to be approximately a quarter of the wavelength at 40 GHz to ensure efficient current distribution while maintaining compact size. A cone half-angle between 30° and 60° was selected to achieve wide impedance bandwidth and stable matching. The feed gap was carefully optimized to minimize capacitive effects and improve return loss performance

2.1 Electromagnetic Simulation and Optimization

ANSYS HFSS was employed to perform full-wave electromagnetic simulations of the antenna. Parametric sweeps were conducted on cone height, base diameter, cone angle, and feed gap to optimize impedance matching and bandwidth. Surface current distributions were analyzed to verify uniform current flow along the cones and to reduce unwanted resonances at millimeter-wave frequencies

Rounded cone tips and symmetrical geometry were incorporated to reduce sensitivity to fabrication tolerances, which are critical at 40 GHz. The optimized structure was evaluated in terms of return loss, VSWR, gain, radiation patterns, and group delay to ensure suitability for broadband radar operation

2.2 Performance Evaluation

The final antenna design was assessed over a wide frequency range to validate its broadband characteristics. The −10 dB impedance bandwidth, radiation behavior, and gain were extracted from simulation results. Both 2D and 3D radiation patterns were analyzed to confirm near-omnidirectional coverage. Group delay analysis was performed to evaluate phase linearity and dispersion, which are critical for pulse-based radar systems

3.Antenna design:

The proposed 40-GHz bicone antenna is designed to achieve wideband impedance matching, mechanical simplicity, and stable radiation for millimeter-wave radar systems. It features two identical metallic cones arranged symmetrically along the vertical axis, fed at their apex via a coaxial feed, as illustrated in Figure 1. This geometry is chosen for its broadband properties and its smooth transition from the feed region to free space. The overall length of the antenna is determined using the following equation.

$$L = 2h + g \quad (1)$$

Where g is the Feed Gap $g = 0.01\lambda_0 \ to \ 0.05\lambda_0$

For Cone Height (h) we use $h = 0.3\lambda$ and for Cone Half-Angle (α) $30^0 \leq \alpha \leq 60^0$.

For the Base Radius of Each Cone (R) equation 2 is used.

$$R = h\tan(\alpha) \quad (2)$$

The main design parameters are the cone height, base radius, cone angle, and feed gap. Initial dimensions were estimated based on classical biconical antenna theory, with the cone angle being the key factor in setting impedance characteristics. A cone angle of 30° to 60° was chosen to naturally produce an impedance close to 50 Ω, minimizing the need for additional matching networks. Each cone's height was selected to be approximately a quarter of the wavelength at 40 GHz, ensuring efficient current distribution while keeping the structure compact. A small gap between the cones allows space for a coaxial probe feed. The inner conductor connects to the upper cone, and the outer conductor contacts the lower cone, creating a balanced transition ideal for high-frequency use. The gap size is optimized to reduce capacitive effects and improve return loss. The antenna is designed with ANSYS HFSS, a full-wave electromagnetic simulation tool used to precisely optimize its performance geometry. Adjustments to cone height, base diameter, and apex sharpness are made to minimize unwanted resonances and expand bandwidth. Surface current analysis shows uniform current flow along the cones, aiding smooth radiation and low reflection.

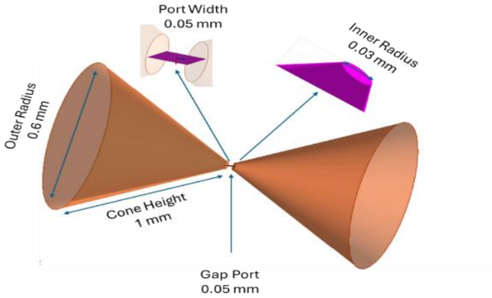

Figure 1: The proposed Bicone antenna for Radar applications.

To reduce fabrication sensitivity at mmWave frequencies, the design incorporates rounded cone tips and a stable, symmetrical support structure. This keeps the footprint compact for easy integration into radar modules. The optimized bicone shape performs strongly at 40 GHz, as shown in the radiation pattern in Figure 2, making it ideal for short-range, high-resolution radar applications.

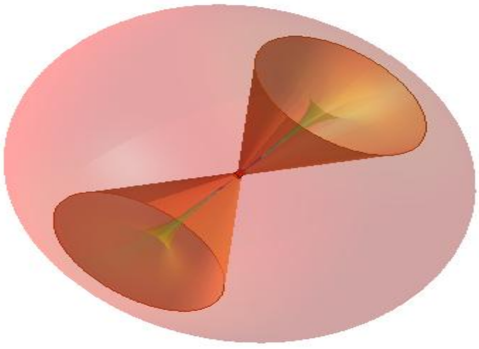

Figure 2: Radiation emitted from the antenna.

The return loss (S_{11}) characteristics of the proposed bicone antenna are illustrated in Figure 3, covering the frequency range from 34 GHz to 46 GHz. The antenna exhibits a well-defined resonance behavior, with the S_{11}curve demonstrating a minimum return loss of approximately –13 dB around the center of the operating band. The –10 dB impedance bandwidth criterion, widely accepted as the threshold for efficient power transfer and adequate radiation performance, is used to quantify the antenna's operational bandwidth. According to the simulation results, the –10 dB points occur at 36.06 GHz and 43.03 GHz, respectively. These two frequencies define the effective operating band of the antenna. The total achievable –10 dB impedance bandwidth can therefore be calculated as:

$$\text{Bandwidth } (BW) = f_{high} - f_{low}$$

$$BW = 43.03\ GHz - 36.06GHz = 6.97\ GHz$$

This corresponds to a relative fractional bandwidth (FBW) of

$$FBW = \frac{f_h - f_l}{f_c} \times 100\ \% = 17.7\%$$

where 39.38 GHz is the center frequency of the band.

Also as illustrated in Figure 3, the bandwidth of approximately 7 GHz confirms the inherently wideband characteristic of bicone antennas, confirming its suitability for millimeter-wave radar applications near 40 GHz. This frequency requires broad impedance matching to accommodate wide instantaneous bandwidths. Moreover, the consistent variation of cap S sub 11ac over the band indicates stable antenna performance with minimal impedance changes, essential for high-resolution radar imaging and broad-spectrum sensing.

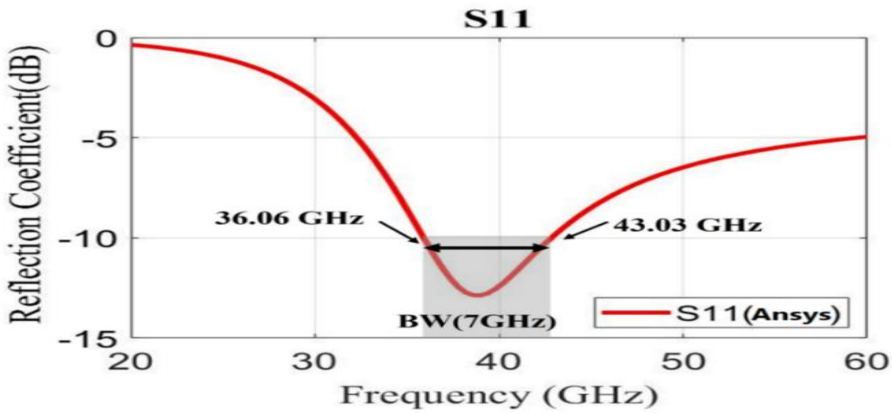

Figure 3: The antenna return loss (S_{11})

This fractional bandwidth verifies that the antenna operates efficiently across a wide portion of the Ka-band, essential for high-frequency radar, imaging, and emerging 6G applications systems. The smooth behavior of the S_{11} curve, with a minimum return loss of approximately −13.5 dB near the center frequency, indicates stable impedance characteristics and efficient power transfer without abrupt resonances or discontinuities. Overall, the measured −10 dB bandwidth of 7 GHz demonstrates that the bicone antenna achieves reliable broadband performance aligned with its geometry. Its broad and continuous operating range makes it ideal for millimeter-wave applications that need low reflection, stable impedance matching, and an extensive spectral range support.Figure 4 shows the 3D far-field gain pattern of the proposed Bicone antenna at 40 GHz. The antenna displays mostly omnidirectional radiation, typical of biconical structures because of their symmetric shape and continuous conical current flow. The maximum realized gain is about 2.28 dBi, indicating slightly better radiation efficiency in that direction while preserving broad angular coverage. The gain surface appears nearly spheroidal, with radiation evenly spread around the azimuth. The smooth shading across most of the surface suggests gain levels between 0 and 2 dBi, reflecting stable radiation without sharp nulls or deep dips. Backward radiation is significantly lower, with the minimum gain around –47.5 dB, showing effective suppression of unwanted radiation and a high front-to-back ratio. The scale confirms consistent mid-to-high gain over a wide angular range, supporting the antenna's wideband and omnidirectional features. This behavior is ideal for millimeter-wave applications requiring uniform coverage, such as short-range radar, broadband sensing, and high-frequency communication. Overall, the 3D gain pattern confirms that the bicone antenna offers stable omnidirectional radiation with moderate directivity and a peak gain of 2.28 dBi, making it well-suited for broadband 40 GHz use.

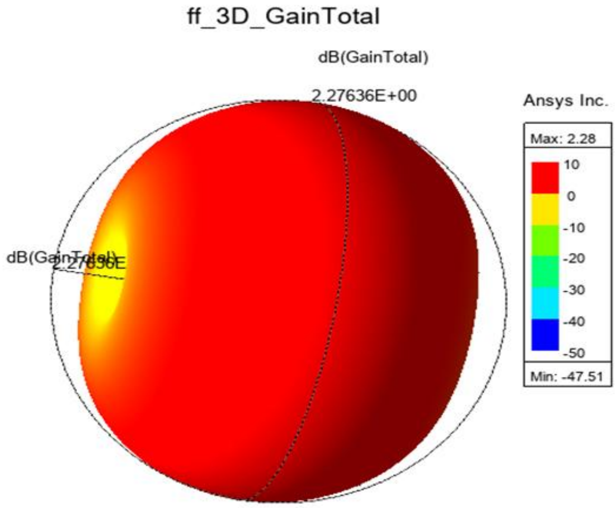

Figure 4: 3-D far-field gain distribution of the proposed Bicone antenna.

The simulated 2D radiation patterns of the Bicone antenna at 40 GHz are depicted in Figure 5. There are two main cut planes at ϕ = 0° and ϕ = 90°. Both patterns display the typical toroidal radiation pattern expected from a biconical structure, due to its symmetry and continuous current distribution along the conical arms. In the ϕ = 0° plane, the gain pattern features two symmetrical main lobes broadside to the antenna axis, with a maximum gain of about 2.26 dBi and deep nulls along the ±180° directions, showing minimal radiation along the antenna's axis. The pattern remains smooth and stable with minimal distortion, indicating efficient current flow around the cones. Similarly, the ϕ = 90° plane shows nearly identical behavior, with main lobes also reaching approximately 2.26 dBi. The high symmetry between these orthogonal cuts confirms the rotational symmetry of the bicone and suggests uniform radiation performance regardless of azimuth angle, which is beneficial for orientation-independent coverage. Both planes feature deep nulls at 0° and 180°, consistent with the behavior of a biconical or dipole-type radiator. The low sidelobe levels and smooth transitions between lobes demonstrate good radiation efficiency and minimal pattern distortion at millimeter-wave frequencies. Overall, the 2D radiation patterns show that the bicone antenna offers stable broadside radiation and consistent angular coverage at 40 GHz, making it suitable for mmWave radar, wide-angle sensing, and short-range communication where reliable and uniform radiation is essential.

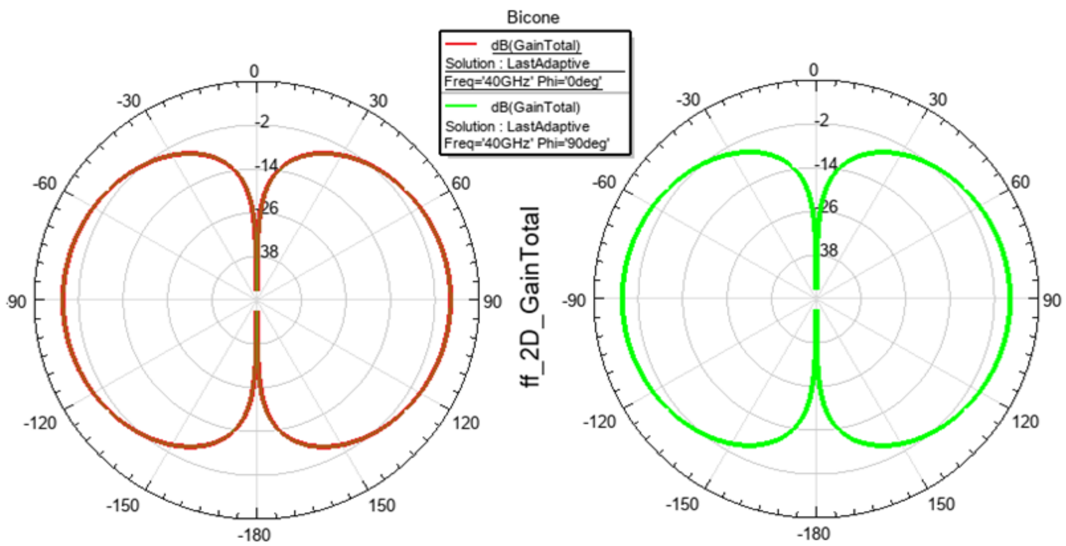

Figure 5: 2-D radiation patterns of the Bicone antenna.

Figure 6 illustrates the simulated Voltage Standing Wave Ratio (VSWR) of the bicone antenna across 20–60 GHz. The antenna shows excellent impedance matching near 40 GHz, with VSWR dropping to about 1.63, well below the threshold of 2, indicating efficient power transfer at the target frequency. The plot reveals a steady improvement in matching as frequency increases from 20 GHz to 40 GHz. At lower frequencies, the higher VSWR indicates poor matching and stronger reflections due to impedance mismatch between the feed line and antenna.

As the frequency nears resonance, the VSWR decreases sharply, reaching a minimum near 40 GHz. Beyond this point, it remains relatively stable with slight increases up to 60 GHz. This smooth trend demonstrates that the bicone antenna maintains consistent impedance characteristics over a broad high-frequency range, a key advantage of biconical designs. The broadband stability supports applications in millimeter-wave radar and sensing, where wide spectral coverage and low reflection losses are critical. Overall, the VSWR results confirm effective impedance matching at 40 GHz and stable broadband performance across the analyzed spectrum.

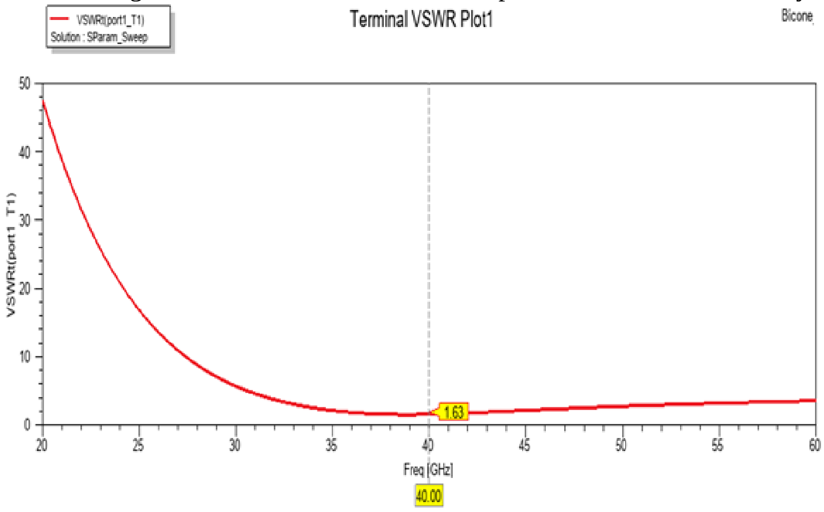

Figure 6: Voltage Standing Wave Ratio (VSWR) of the bicone antenna.

Figure 7 illustrates the simulated group delay of the bicone antenna across the 20–60 GHz frequency spectrum. Group delay is crucial for wideband and radar applications because it indicates how consistently different frequency components of a signal propagate through the antenna. A stable or slowly varying group delay is desirable, as it ensures accurate time-of-flight measurements, improved range resolution, and reduced pulse distortion. The plot shows that the group delay varies smoothly and continuously throughout the entire frequency range, with no abrupt jumps or spikes. This consistency confirms that the antenna does not introduce significant dispersive effects, highlighting one of the key advantages of broadband biconical designs. From 20 GHz to approximately 37 GHz, the group delay slightly increases from about –220 dB to –205 dB, reflecting an improved phase response as the antenna approaches resonance.

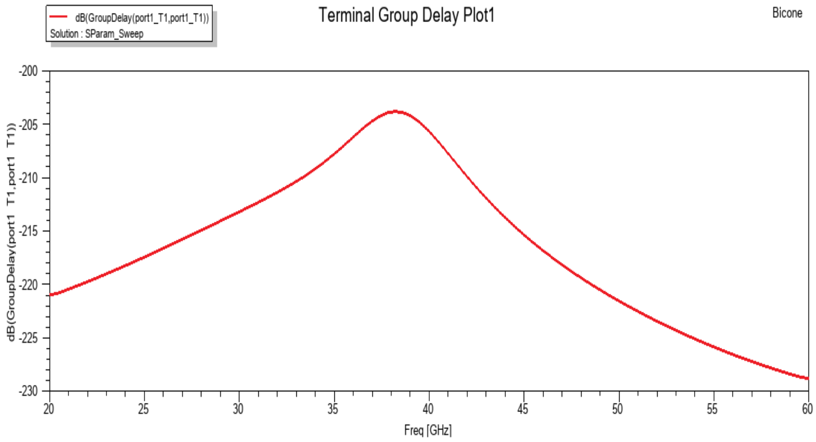

Figure 7: group delay of the bicone antenna.

A peak in group delay appears near 40 GHz, matching the antenna's targeted frequency. This usually indicates optimal impedance matching and efficient power transfer, as also shown by the VSWR and S_{11} results. While the group delay slightly rises at resonance, the increase is smooth and does not cause distortion, indicating stable phase behavior in the 40-GHz range. Beyond this frequency, the group delay gradually declines while remaining smooth. There are no sharp fluctuations or resonant anomalies across the entire band, confirming the antenna's consistent, low-dispersion performance outside the main operating range. Overall, the group delay data demonstrate that the bicone antenna provides excellent phase linearity and minimal distortion around 40 GHz, making it suitable for mmWave radar, pulse detection, and wideband communication systems that need clean time-domain signals.

4. Discussion and comparison:

Table 1 previous and current works comparison.

Antenna Type	Operating Frequency (GHz)	−10 dB Bandwidth	Peak Gain (dBi)	Radiation Pattern	Remarks	
Classical Bicone	Broadband (theoretical)	Very wide (theoretical)	~2–3	Omnidirectional	Fundamental reference for Bicone antenna theory	[1]
Planar Antenna	30–40	Narrow (<10%)	5–7	Directional	Limited bandwidth requires a substrate	[8]
Compact mmWave Antenna	38–42	~8–10%	3–6	Semi-directional	Higher gain but narrower bandwidth	[9]
Wideband Bicone	26–40	Wide (>15%)	~2	Omnidirectional	Confirms the broadband nature of Bicone antennas	[7]
mmWave Antennas (Survey)	>30	Application-dependent	Varies	Varies	Highlights fabrication and loss challenges	[6]
Bicone Antenna	36.06–43.03	≈ 7 GHz (17.7%)	2.28	Nearly omnidirectional	Simple structure, wideband, suitable for short-range radar	This Work

As shown in Table 1, the proposed 40-GHz Bicone antenna exhibits a wider impedance bandwidth than most planar and compact mmWave antennas reported in the literature. While directional antennas and arrays offer higher gain, they typically suffer from increased complexity and reduced bandwidth. The proposed design provides a balanced trade-off between bandwidth, radiation stability, and structural simplicity, making it well-suited for short-range millimeter-wave radar applications.

4. Challenges:

Despite the promising simulated performance of the proposed 40-GHz Bicone antenna, several challenges must be acknowledged. One major challenge is its high sensitivity to fabrication tolerances at millimeter-wave frequencies. At 40 GHz, slight deviations in cone angle, feed gap, or surface roughness can significantly impact impedance matching and radiation characteristics. Achieving precise mechanical dimensions during practical fabrication can therefore be difficult and costly. Another issue involves material losses and surface effects on the conductor at mmWave frequencies. Losses from finite conductivity, skin effect, and dielectric substrates can decrease radiation efficiency and the realized gain compared to ideal simulation results. These losses become more significant as frequency increases and must be carefully considered in real-world applications. The proposed design has only been validated through Ansys HFSS full-wave electromagnetic simulations. Without experimental measurements, real-world factors such as connector losses, assembly imperfections, and environmental influences are not yet accounted for. This can cause differences between simulated and actual performance. Additionally, while the antenna offers broad bandwidth and omnidirectional radiation, its moderate gain (≈2.28 dBi) may be insufficient for long-range radar or applications requiring higher directivity. This limits its use mainly to short-range sensing systems unless further enhancement techniques are employed.

Conclusion

This paper presents the design and full- wave electromagnetic analysis of a compact Bicone antenna optimized for 40- GHz millimeter- wave radar applications. The antenna geometry was carefully designed by adjusting key parameters such as cone angle, height, and feed gap to achieve wideband impedance matching, stable radiation characteristics, and mechanical simplicity suitable for high- frequency operation. The inherent broadband nature of the biconical structure was effectively utilized to meet the strict requirements of modern short- range radar systems. Simulation results show that the proposed antenna attains a- 10 dB impedance bandwidth of approximately 7 GHz, spanning from 36.06. 91 GHz to 43. 03 GHz, corresponding to a fractional bandwidth of about 17. 7%. This wide bandwidth ensures reliable radar performance and supports high range resolution. The return loss and VSWR results confirm good impedance matching at the target frequency, with a minimum VSWR of 1.63 at 40 GHz, indicating efficient power transfer and low reflection. The radiation performance analysis reveals that the antenna maintains stable, nearly omnidirectional radiation characteristics, which are highly desirable for short- range radar and sensing applications. The simulated peak realized gain of around 2. 28 dBi, combined with smooth 2 D and 3 D radiation patterns, demonstrates consistent angular coverage with minimal sidelobe distortion. Additionally, the group delay response is smooth and well- behaved across the operating band, indicating low dispersion and good phase linearity- both critical for pulse- based radar systems and precise time-domain measurements. Overall, the results validate that the proposed Bicone antenna offers an effective combination of wide bandwidth, stable radiation, low profile, and simple geometry, making it a strong candidate for next- generation 40- GHz millimeter- wave radar systems. Future work may include experimental validation, integration with radar front- end circuits, and extending the design toward array configurations to further enhance gain and directional control.

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