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2채널 밀리미터파 대역 내 양방향 통신을 위한 SIW 기반 Cavity-Backed 타원형 슬롯 2×2 안테나 배열

SIW-Based Cavity-Backed Elliptical Slot 2×2 Antenna Array for Two-Channel mm-Wave In-Band Full-Duplex Communication

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요 약

본 논문에서는 단일층 Taconic RF-60TC 기판에 제작된 기판 집적 도파관(SIW) 기반 공동-배면형 타원 슬롯 안테나 어레이를 제안한다. 타원 슬롯은 밀접하게 배치된 다중 공진 모드를 효율적으로 여기하여 광대역 임피던스 정합을 제공하며, 높은 유전율 기판은 안테나의 소형화를 가능하게 한다. 또한, SIW 공동-배면 구조는 후방 로브 방사를 억제하여 효율을 향상시킨다. 2×2 차동 급전 안테나 어레이와 1×4 SIW 기반 차동 전력 분배기를 통합하여 제작 및 측정하였으며, 시제품은 56～65.3 GHz에서 −10 dB 반사 대역폭과 11.15 dBi의 최고 실현 이득을 달성하였다. 제안된 안테나는 소형, 광대역 및 고성능 mm-Wave 인밴드 풀 듀플렉스 통신에 적합함을 확인하였다.

Abstract

This paper presents a substrate-integrated waveguide (SIW)-based cavity-backed elliptical slot antenna array fabricated on a single layer of a Taconic RF-60TC substrate. The elliptical slot enables wideband impedance matching by exciting multiple closely spaced resonant modes, and the high-permittivity substrate facilitates a compact antenna design. The SIW cavity-backed structure suppresses backlobe radiation and enhances the efficiency. A 2×2 differentially fed antenna array integrated with a 1×4 SIW-based differential power divider was fabricated and tested. The prototype demonstrated a −10 dB reflection bandwidth over 56～65.3 GHz, with peak realized gains of 11.15 dBi, proving suitable for compact, wideband, high-performance mm-Wave in-band full-duplex communication.

Key words: Substrate-Integrated-Waveguide (SIW), Millimeter-Wave (mm-Wave), Cavity-Backed Elliptical Slot Antenna

Ⅰ. Introduction

The rising demand for systems that allow simultaneous transmission and reception is evident in advanced wireless communication, providing advantages such as higher data throughput and efficient spectrum utilization[1]. A key challenge, however, is achieving high isolation between the transmitter and receiver to mitigate self-interference. Furthermore,

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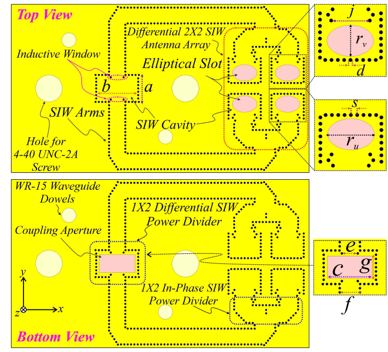
for communication at higher frequencies high-gain antennas are essential to reduce free-space attenuation, which reaches its maximum at 60 GHz due to oxygen absorption (15 dB/km). A single-ended fed 60 GHz 2×2 SIW array achieved 7～11.9 dBi gain but had a suboptimal −7 dB reflection coefficient for 54.5～62 GHz[2].

This paper introduces a cavity-backed elliptical slot antenna using a single-layer SIW structure. The in-band full-duplex communication scenario is evaluated through simulations using two modules. For performance validation the proposed 2×2 antenna array integrated with a 1×4 SIW-based power divider is fabricated. The fabricated prototype achieves a 16.61 % reflection bandwidth (S_{11}<−10 dB) with a peak gain of 9.7～11.5 dBi, making it suitable for 2-channel in-band full-duplex mm-Wave communication.

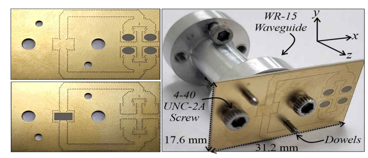
Ⅱ. Antenna Geometry and Operating Principle

The proposed antenna, shown in Fig. 1 with parameters in the caption, utilizes a single layer of Taconic RF-60TC substrate (εr=6.15, tanδ=0.002 @ 10 GHz) with a thickness of 0.51 mm. The SIW arms and cavity are constructed by connecting the top and bottom metal layers through series of via, with each via having a diameter d and spacing s, ensuring s ≤ 2d to maintain radiation loss below −0.06 dB across the V-band. An elliptical slot with major and minor radii r_u and r_v is etched into the top metal of the SIW cavity, with dimensions initially chosen to support the fundamental eigenmode of the resonant cavity and further optimized using full-wave EM simulation in HFSS for better performance. Fig. 2 shows design evolution steps for the proposed 2×2 differential-fed antenna array.

The initial design featured an SIW-based cavity-backed rectangular slot antenna (Fig. 2(a)), which exhibited a narrow bandwidth with a single resonance at 60 GHz (Fig. 3(a)). By modifying the slot into an elliptical shape with major and minor radii r_u and r_v (Fig. 2(b)), multiple resonant modes were excited, resulting in a wider bandwidth (Fig. 3(a)). The



(a) 제안된 2×2 안테나 배열 레이아웃
(a) Proposed 2×2 antenna array layout



(b) 제작된 2×2 안테나 제작 프로토타입
(b) Proposed 2×2 antenna fabricated prototype

그림 1 제안된 캐비티 백 슬롯 안테나의 기하학적 구조
Fig. 1. Geometry of proposed 2×2 antenna array (a=3.0, b=4.4, c=3.7, d=0.2, s=0.35, e=1.4, f=1.7, g=1.9, j= 2.14, r_u=2.6, r_v=1.7).

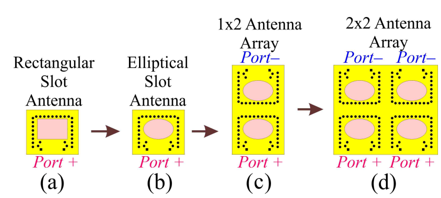
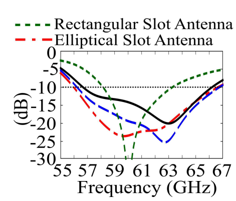
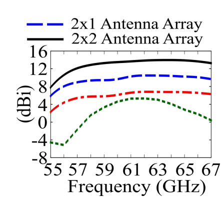


그림 2 제안된 안테나 배열 설계 과정
Fig. 2. Proposed antenna array design evolution steps.



(a) 시뮬레이션된 S_{11}
(a) Simulated S_{11}



(b) 시뮬레이션된 이득
(b) Simulated realized gain

그림 3 설계 발전 단계에 대한 시뮬레이션 결과
Fig. 3. Simulation results for design evolution steps.

elliptical slot's smooth aperture field distribution and lower Q-factor improved radiation efficiency and impedance match-

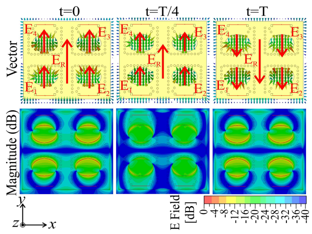
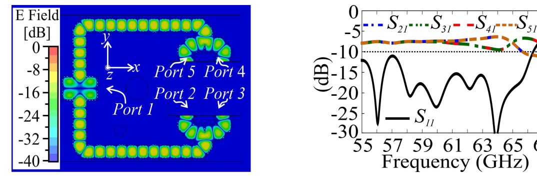


그림 4 제안된 배열의 60 GHz에서의 전기장 분포
Fig. 4. Proposed array electric field distribution at 60 GHz.

ing, leading to enhanced gain across the extended bandwidth (Fig. 3(b)). For further gain improvement, a 1x2 array was designed by vertically mirroring the single element with 3.25 mm spacing (Fig. 2(c)), and differential out-of-phase excitation ensured broadside radiation , boosting gain by over 3.5 dB (Fig. 3(b)). Finally, a 2×2 differentially fed array was developed with horizontal and vertical element spacing of 4.5 mm (0.9 λ at 60 GHz) and 3.25 mm (0.65 λ at 60 GHz), respectively (Fig. 2(d)). The horizontal elements were fed in-phase, while the vertical elements were fed out-of-phase. The optimized array achieved S_{11}<−10 dB across 56.7～66 GHz and a realized gain of 11.75～13.9 dBi, as shown in Fig. 3(b). The electric field distribution at 60 GHz, depicted in Fig. 4, illustrates the proposed array operating principle. Differential excitation aligns the electric field in the broadside direction, optimizing radiation, with stronger intensity observed along the elliptical slot's edges. As the phase progresses from 0° to 180°, the field direction reverses, confirming linear polarization.

Ⅲ. 1×4 SIW-based Differential Power Divider

To excite the proposed 2×2 differential antenna array, a 1×4 SIW-based differential power divider was designed on the same Taconic RF-60TC substrate. Energy is coupled from the WR-15 waveguide to the SIW cavity through an aperture in the ground plane, with dimensions matching those of the WR-15 waveguide. It is then transferred to the SIW arms via an inductive window, whose width is chosen to support TE_{10} mode propagation, as shown in Fig. 5(a) by the



(a) 60 GHz에서의 전기장 분포 (b) 시뮬레이션된 *S*-파라미터
(a) E-field distribution (60 GHz) (b) Simulated *S*-parameters

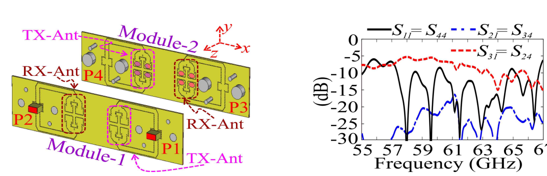
그림 5 제안된 배열의 60 GHz에서의 전기장 분포
Fig. 5. E-field distribution and *S*-parameters of feeding network.

electric field distribution at 60 GHz. An E-plane T-junction generates differential signals, which are further divided by 1×2 in-phase SIW power dividers, producing four arms. Two of these have in-phase signal and other two have out-of-phase, ensuring optimal excitation of the 2×2 array.

Fig. 5(b) shows that the optimized power divider achieves a reflection coefficient below −10 dB across 57～64 GHz, with a transmission coefficient of approximately −7.4 dB at 60 GHz. Phase analysis confirms accurate signal distribution, with ports 1 and 2 in-phase and ports 3 and 4 showing a 180° phase shift, ensuring precise differential excitation.

Ⅳ. In-Band Full-Duplex Communication

Fig. 6(a) depicts an in-band full-duplex communication setup in HFSS software with Module 1 and Module 2 placed face to face, each equipped with TX and RX antennas. Antenna 1 (TX) in Module 1 transmits to Antenna 3 (RX) in Module 2, while Antenna 4 (TX) in Module 2 transmits to Antenna 2 (RX) in Module 1. The TX-RX spacing within each module is 10 mm (～2 λ at 60 GHz), and the in-



(a) 시뮬레이션 설정 (b) 시뮬레이션된 *S*-파라미터
(a) Simulation setup (b) Simulated *S*-parameters

그림 6 동일 대역 전이중 통신
Fig. 6. In-band full-duplex communication.

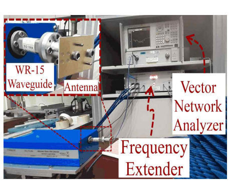
ter-module distance is 5 mm (~1 λ at 60 GHz).

Fig. 6(b) shows *S*-parameters, demonstrating excellent performance. Reflection coefficients (S_{11}=S_{44}) are well- matched, and isolation (S_{21}=S_{34}) is −22.6 dB, ensuring minimal interference. Transmission coefficients (S_{31}=S_{24}) achieve −6.4 dB at 60 GHz, with an overall reflection coefficient of −9 dB, both suitable for this application. These results highlight the antenna's potential for in-band full-duplex communication in the 60-GHz band.

Ⅴ. Experimental Results for Proposed 2×2 Antenna Array

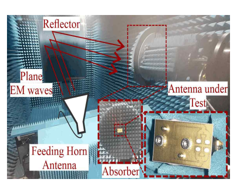
For performance validation, the proposed 2×2 differential antenna array with feeding network was fabricated and subsequently tested for reflection coefficient and far-field radiation as shown in Fig. 7(a) and Fig. 7(b) respectively.

The measured reflection coefficient bandwidth was 16.61 % (S_{11}<−10 dB) from 56 to 65.3 GHz, closely corresponding the simulated 18.73 % bandwidth (55.85~65 GHz) as shown in Fig. 7(c). The measured gain ranged from 9.7 dBi to 11.5 dBi, consistent with the simulated range of 10.45 dBi to 11.6 dBi (Fig. 7(d)). Resonance points observed in S_{11} curve and gain reductions were caused by feeding network losses, fabrication tolerances, and changes in substrate permittivity and loss tangent, as per Debye model.



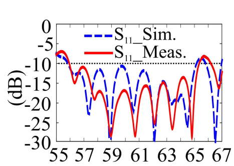
(a) S_{11} 측정 환경

(a) S_{11} measurement setup



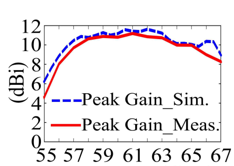
(b) 원거리 영역 측정 설정

(b) Far-field measurement setup



(c) 시뮬레이션 및 측정된 S_{11}

(c) Simulated and measured S_{11}



(d) 시뮬레이션 및 측정된 이득

(d) Simulated and measured gain

그림 7. 제안된 안테나의 측정 구성 및 결과

Fig. 7. Measurement setup and results of proposed antenna.

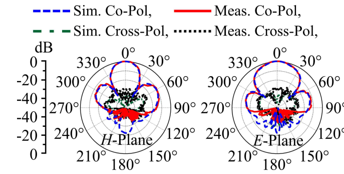


그림 8 60 GHz에서의 정규화된 방사 패턴

Fig. 8. Norrmalized radiation pattern at 60 GHz.

Fig. 8 shows normalized radiation patterns at 60 GHz along the H-plane (xz-plane) and E-plane (yz-plane), with strong agreement between measured and simulated results. The antenna also achieves a broadside cross-polarization level below −20 dB. The sidelobe level can be further reduced by decreasing inter-element spacing to mitigate interference in in-band full-duplex communication.

Ⅵ. Conclusion

A compact 2×2 SIW-based elliptical slot antenna with a differential feeding network is designed and fabricated on a single-layer Taconic RF-60TC substrate. The antenna achieves a wide reflection bandwidth of 16.61 % (56~65.3 GHz for S_{11}<−10 dB) and a gain of 9.7~11.5 dBi. In-band full-duplex communication is evaluated through simulations at a 5 mm (~4 λ) spacing. The differential feeding ensures symmetric broadside radiation, low sidelobes, and improved inter-element isolation, making it suitable for 60-GHz two-channel in-band full-duplex communication.

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