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Via-Monopole Based Quasi Yagi-Uda Antenna for W-Band Applications using Through Glass Silicon via (TGSV) Technology

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ABSTRACT This paper presents a W-band planar type via-monopole based quasi Yagi-Uda antenna using metal coated through glass silicon via structures. The antenna was designed and fabricated on 350 μm thick borosilicate glass substrate, which has very low dielectric loss compared with silicon at millimeter-wave frequencies. We used a microstrip line to feed the antenna, and the Yagi-Uda configuration using via structured radiator; reflectors; and director were fabricated using tungsten coated silicon via structures embedded in reflowed glass substrate with good high frequency characteristics. The proposed antenna achieved vertical polarization in planar configuration with height 0.09λo. High gain with end-fire radiation was achieved due to the Yagi-Uda configuration. Measured results confirmed the fabricated antenna operated in the W-band with 10 dB fractional bandwidth (FBW) of 12.5% from 76.3 to 86.5 GHz and peak gain of 7.82 dBi at 81 GHz in the end-fire direction. Thus, the proposed antenna with end-fire radiation will be useful for millimeter-wave onboard wireless communication, radar imaging, and tracking applications.

INDEX TERMS Borosilicate-glass, end-fire, Yagi-Uda antenna, through glass silicon via (TGSV).

I. INTRODUCTION

With the ongoing development of modern communication systems, there has been growing demand for high Gbps data rates [1]; since bandwidth is directly proportional to communication data rates [2]. Therefore, radio frequency (RF) front ends operating at frequencies above 70 GHz or higher have attracted considerable research attention [3], [4]. High atmospheric absorption at these frequencies make them suitable for high speed short range communication, requiring antennas with high gain for W-band applications, such as high resolution radar imaging, remote sensing and high speed wireless communication [5], [6]. Signal-to-interference-plus-noise ratio (SINR) generally decreases at high frequencies due to extreme free space loss. Therefore, suitable antennas are critical to meet challenging requirements. Highly directional antennas and line-of-sight (LOS) communication can greatly alleviate these problems, hence there is increasing demand for the low cost compact printed antennas [7]–[9].

Yagi-Uda antennas comprise a single radiator and reflector, and one or more directors [10]. These antennas are capable of end-fire radiation with very high gain due to the reflector and director and can filter signal noise in the opposite direction close to zero. Many configurations have been proposed for printed Yagi-Uda antennas over the last two decades [9], [11]–[29], with the first Yagi-Uda antenna in microstrip technology proposed by Huang in 1989, comprising four patches: one reflector, one driven element, and two directors. The patches were electromagnetically coupled to create a steering beam [10]. A co-planar-waveguide (CPW)-fed planar quasi Yagi-Uda antenna was subsequently proposed [13] with 44% impedance bandwidth and 7.4 dBi gain; and a printed Yagi array antenna with high front-to-back (F/B) ratio (up to 15 dB) [21], with 10.5 dBi gain and 10% measured impedance bandwidth. Reference [22] proposed a microstrip-fed Yagi-Uda antenna with wide impedance bandwidth (48%) and high radiation efficiency, and [24] proposed

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a differentially-fed millimeter-wave Yagi-Uda antenna with folded dipole feed. A 7-element antenna with 8–10 dBi gain over 22–26 GHz was achieved. Reference [29] fabricated a 4×4 stacked Yagi array antenna at 60 GHz with 11 dBi measured gain over 4.2% bandwidth. Reference [30] fabricated a millimeter-wave on-chip Yagi antenna using 0.18 μm CMOS technology. Reference [16] proposed a W-band cylindrical monopole vertically mounted on a glass substrate for low cost wireless communication systems. Thin wire or cylindrical monopoles have broad impedance bandwidths and hence provide better candidates for broadband operation.

Fully integrated millimeter-wave communication systems have been highly researched over the last decade. Consequently, through silicon vias (TSVs) [31] have become important components due to the increasing number of input and output (I/O) devices in integrated millimeter-wave communication systems [30], due to their various advantages, such as small footprint, high density, and low power (3D) stacking integration. Conventional silicon substrates have been widely proposed as conventional RF substrate replacement for on-chip or in-package forms [31], [32] due to their shorter signal paths, ease of wafer processing, and die matched coefficient of thermal expansion (CTE). However, silicon interposers with TSV technologies have various limitations, including high electrical substrate losses, fabrication cost, and process complexity.

Glass interposers with through-glass vias (TGVs) have been widely studied [4], [6], [33]–[35], due to their excellent electrical properties, such as low substrate losses at high frequency, CTE adjustability, fine line spacing, availability of large and ultra-thin panels, and low material and manufacturing cost [5], [31], [33]. Thus, glass interposers are the current best option to replace conventional silicon interposers and provide an attractive platform for high frequency, RF, microwave passive components and packaging.

This paper reports a W-band microstrip line fed via-monopole based quasi Yagi-Uda antenna with vertical polarization and end-fire radiation in planar configuration on a glass substrate. We show that vertical polarization is less prone to path loss, which makes vertical wire antennas suitable candidates to achieve better radiation performance as well as high security. The via-monopole configuration was realized using novel metal coated through-glass silicon via (TGSV) technology, as shown in Fig. 1.

The proposed antenna was designed and fabricated on a 350 μm thick borosilicate glass substrate, which has a very low dielectric loss compared to silicon for millimeter-wave bands. Metal coated TGSVs were fabricated by microfabrication based on deep silicon etching and glass reflow, and can effectively substitute for metallic vias in conventional TGVs without degrading antenna performance. The proposed antenna's performance was numerically and experimentally demonstrated.

The remainder of this paper is organized as follows. Sections II and III discuss the Yagi-Uda antenna design and fabrication, respectively. Section IV discusses simulated and experimental results for the proposed antenna, and Section V summarizes and concludes the paper, and discusses proposed ongoing research.

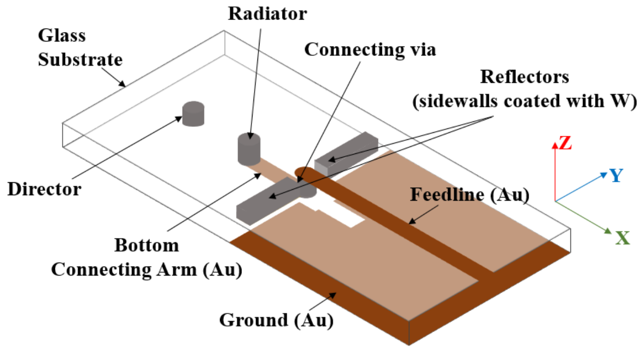

FIGURE 1. Proposed antenna perspective view.

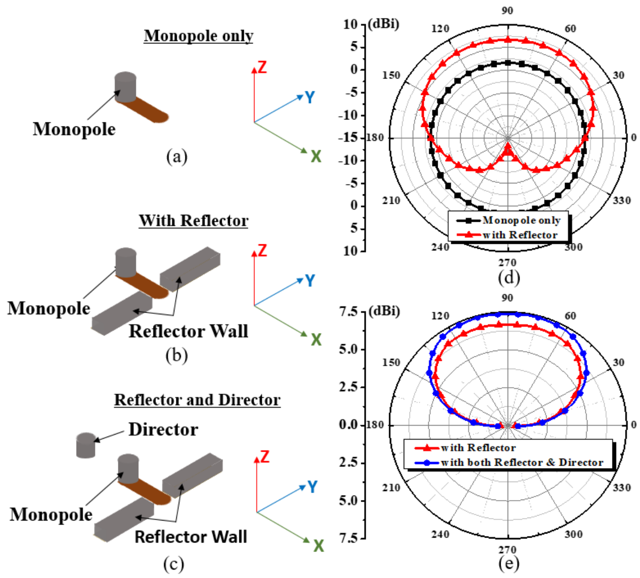

FIGURE 2. Geometry for (a) monopole only, (b) monopole with reflector, and (c) monopole with reflector and director; and simulated two-dimensional far-field radiation pattern at 81 GHz for (d) monopole with reflector, and (e) monopole with reflector and director.

II. ANTENNA DESIGN

Fig. 1 shows the proposed quasi Yagi-Uda antenna configuration with embedded TGSV monopole in the glass interposer layer, comprises a radiator, director, and truncated ground plane along with two via-walls as reflectors. The proposed antenna was designed on an ultra-thin (350 μm thick) borosilicate glass substrate having a thickness of 350 μm with a permittivity and a tangent loss of 4.6 and 0.0037, respectively.

Fig. 2(a) shows the proposed antenna concept, based on embedded vertical via-monopole in the glass interposer. The radiator was a silicon via-monopole with the same height as the substrate thickness coated with tungsten metal and feeder line connecting the radiator to increase the current on electrically short monopole compared to a quarter wavelength ($\lambda/4$)

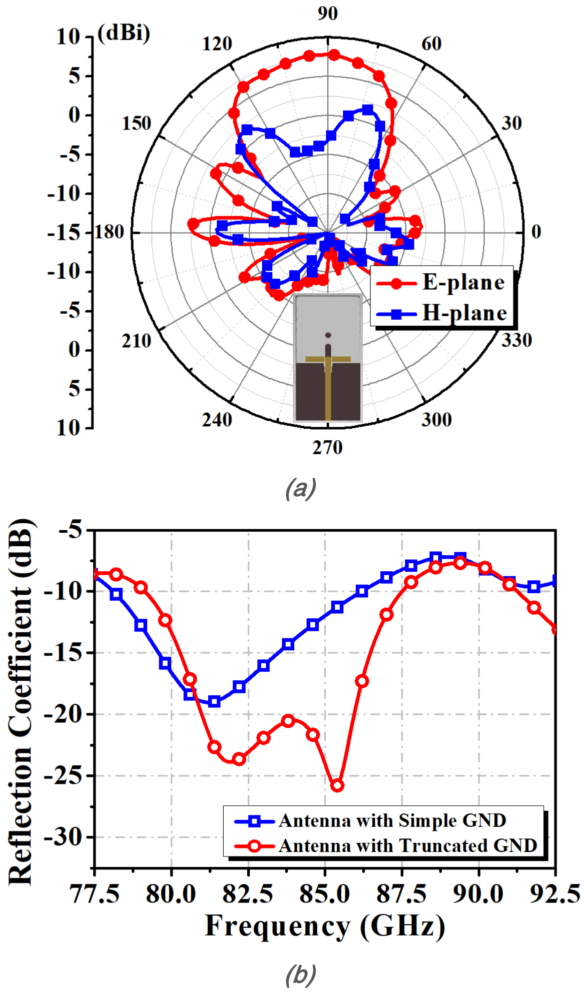

FIGURE 3. (a) Simulated 2-D radiation pattern in E- and H-planes at 81 GHz. (b) Reflection coefficient plot with and without truncated ground.

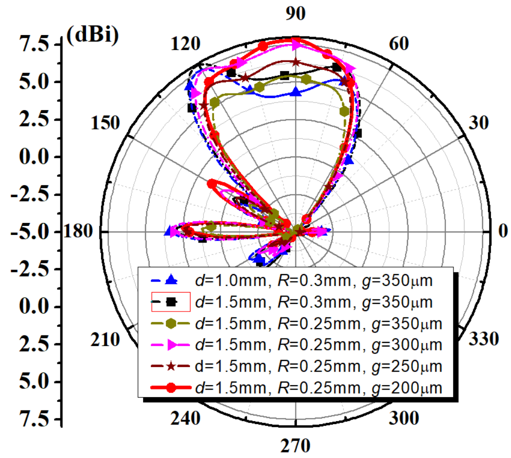

FIGURE 4. Simulated two-dimensional radiation pattern at 81 GHz with different R, g, and d.

TABLE 1. Optimal proposed quasi Yagi-Uda antenna dimensions.

Parameter	L	W	S_w	S_l	f_w	f_l
Value (mm)	15	7	0.65	0.7	0.526	7.3
Parameter	r_w	r_l	G_l	R	d	t
Value (mm)	0.5	2	6.9	0.263	1.5	0.35

monopole antenna for W-band. Fig. 2(d) shows simulated two-dimensional radiation pattern for a via-monopole in the XY-plane. We included the reflector via-wall on the rear side of the radiator to reduce backward radiation while enhancing the forward end-fire radiation beam, as shown in Fig. 2(b). Thus, back radiation was reduced by 14 dB, while enhancing forward end-fire gain to 6.7 dBi, as shown in Fig. 2(d).

Figs. 2(c) and (e) show the director via introduced ahead of the radiator to enhance antenna gain by 7.4 dBi according to the Yagi-Uda principle. The antenna was fed by a microstrip line with a modified ground plane on the rear bottom side, with an extra via to connect between the microstrip and feeder line.

Fig. 3(a) shows the proposed antenna radiation was vertically polarized in the XZ-plane since the electric-field (E-field) coincides with the vertical plane. The modified ground plane acted as a reflector and was truncated in the middle to provide broadband impedance matching, as shown in Fig. 3(b). The design steps for the proposed quasi Yagi-Uda antenna can be summarized as follows.

1) Compute the quarter wavelength of the monopole for W-band around 80 GHz.
2) Design a via-monopole with height t, the glass substrate thickness.
3) Load a capacitive feeder line at the tip of the monopole antenna to improve efficiency, since $t = 350\ \mu$m is insufficient height for quarter wavelength monopole antenna working at 80 GHz.
4) Place a reflector via wall on the rear side of the radiator, since the monopole has omni-directional radiation pattern, it reduces the backward radiation while enhancing the forward end-fire radiation beam.
5) One director via was placed ahead of the radiator via with reduced height $g = 0.05\lambda_o$, to further increase gain.
6) Select microstrip feed followed by a W-band connector.
7) Modify the ground plane to act as a reflector on the rear side, truncated in the middle to provide impedance matching over a wide range of frequencies.

As discussed above, the proposed antenna used the Yagi-Uda principle, which can be specified using only a few parameters: via-monopole radius, R; director height, g, and distance between radiator and director, d to achieve high directivity, as shown in Fig. 4. For example, when $d = 1.0$ mm the main beam split into two lobes offset relative to the end-fire direction. Optimization and fine tuning provided optimal $d = 1.5$ mm (spacing between radiator and reflector wall and between radiator and director), $R = 0.25$ mm, and $g = 0.2$ mm.

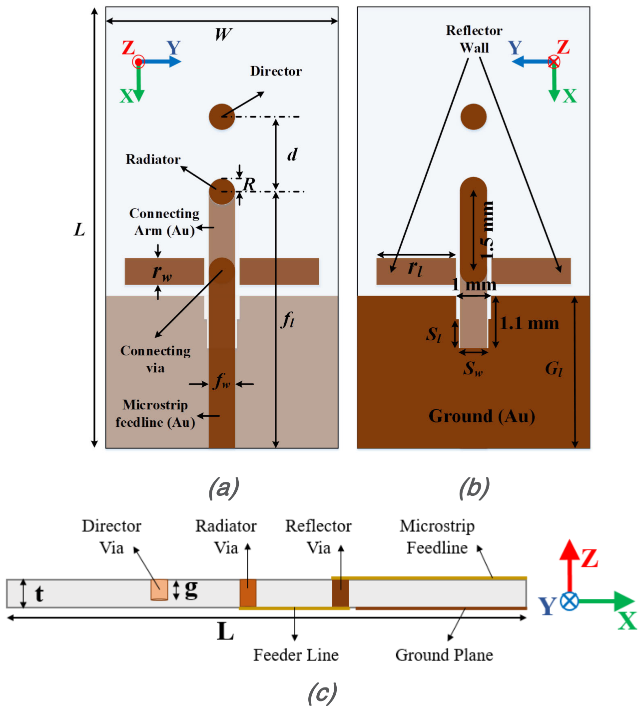

FIGURE 5. Proposed Yagi-Uda antenna configuration (a) top, (b) bottom, and (c) side views.

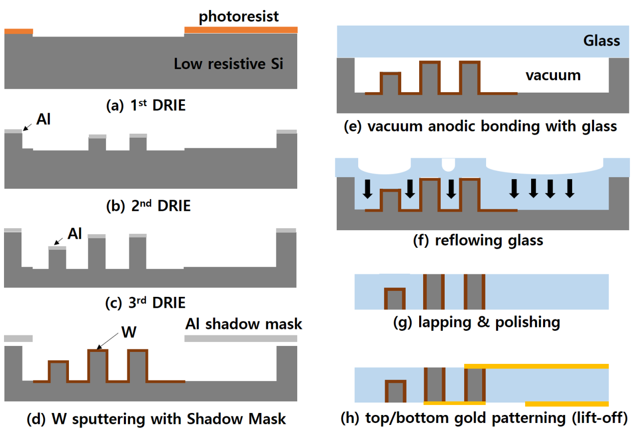

FIGURE 6. Proposed antenna fabrication process.

The proposed antenna was designed and verified using the ANSYS high-frequency structure simulator (HFSS). Table 1 shows the final optimal dimensions for prototype fabrication, and Fig. 5 shows top and bottom view for the designed antenna.

III. ANTENNA FABRICATION

Our previous work proposed a planar helical antenna [8] fabricated using TGSV technology based on deep reactive ion etching (DRIE) of silicon, selective metal coating, and glass reflow, which is similar to the process developed in our group [36]. In the previous case, a single silicon DRIE process was sufficient to fabricate TGSVs since all TGSV

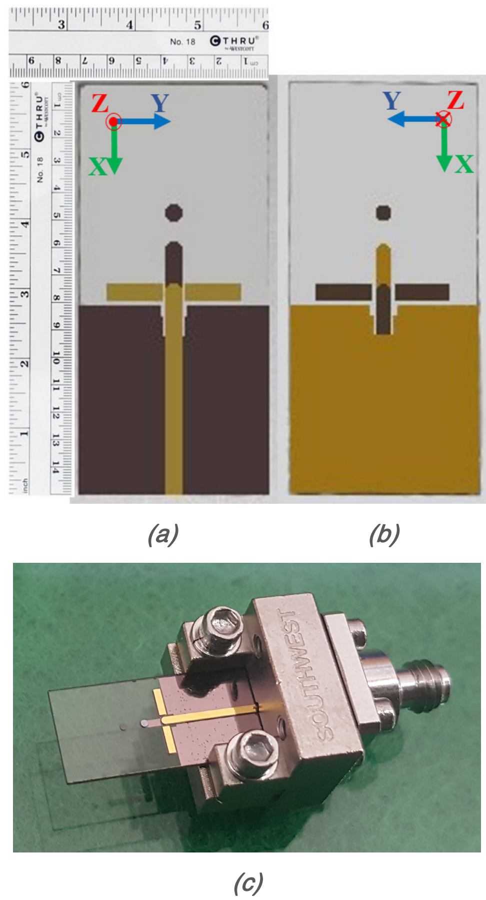

FIGURE 7. Final fabricated prototype of proposed Yagi-Uda antenna (a) top and (b) bottom view; (c) antenna with the W-band connector.

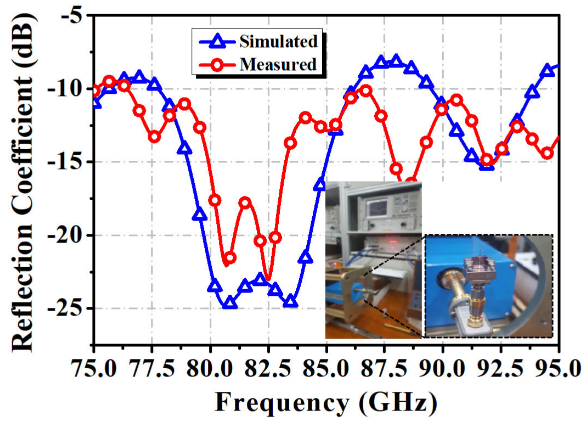

FIGURE 8. Simulated and measured reflection coefficient plots.

heights were the same as the substrate thickness. In contrast, the current case used multi-step silicon DRIE and single glass reflow to fabricate TGSVs with two different heights in a single glass substrate.

Fig. 6 shows the proposed quasi Yagi-Uda antenna fabrication process. We first use a short DRIE of silicon employing a photolithographically patterned photoresist mask (AZ P4330-RS) to form a 3 μm deep shallow cavity,

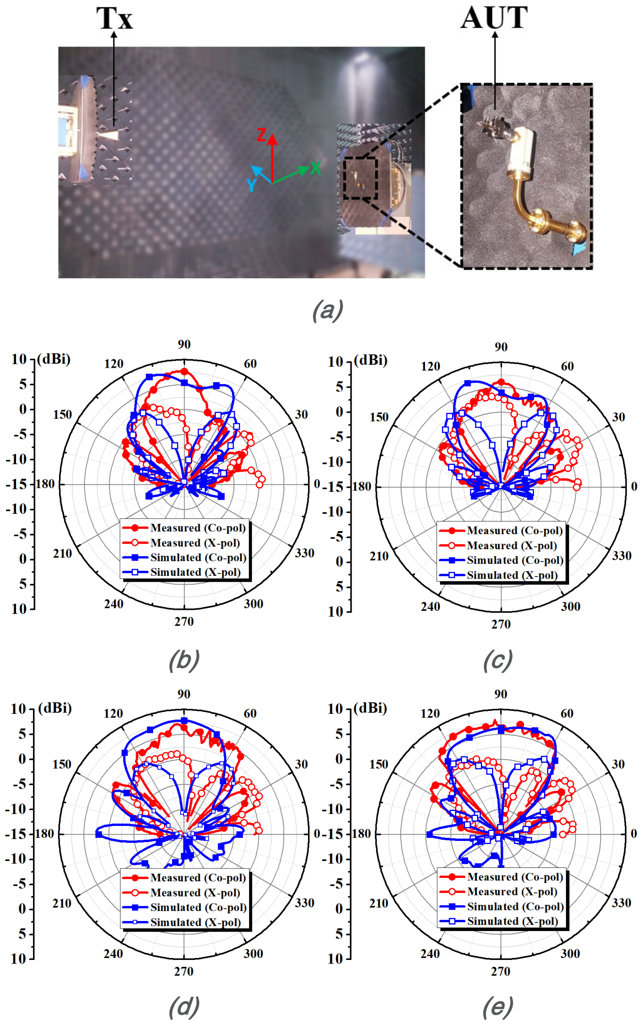

FIGURE 9. (a) Photo of the radiation pattern measurement setup. Measured 2-D far-field radiation patterns: (b) 77 GHz, (c) 79 GHz, (d) 81 GHz, and (e) 83 GHz.

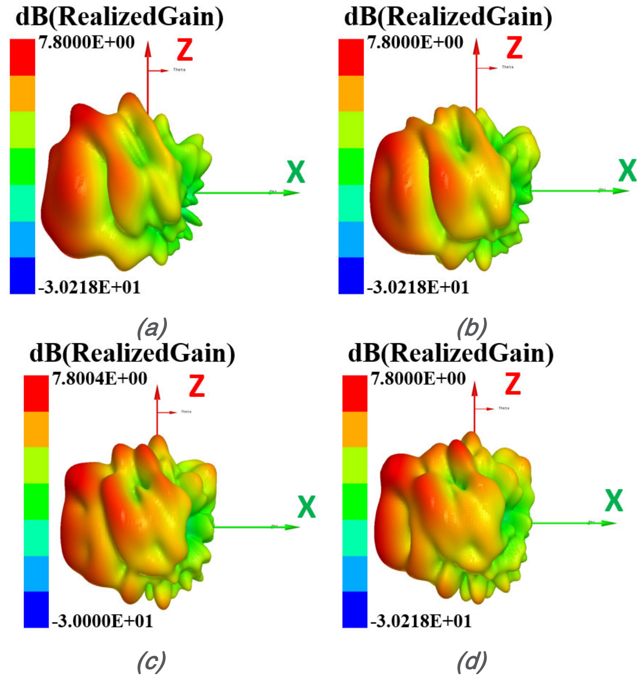

FIGURE 10. Simulated three-dimensional far field radiation pattern at (a) 77, (b) 79, (c) 81, and (d) 83 GHz.

which is required for later anodic bonding of the glass near the silicon via regions (Fig. 6(a)). We used a 4-inch, 525 μm thick boron doped p-type low resistive silicon wafer with 0.01$\sim$0.02 Ω·cm resistivity to minimize via losses. After stripping the photoresist in acetone, a 0.2 μm thick aluminum layer was e-beam evaporated and patterned inside the cavity by wet etching with a PAN solution (phosphoric, acetic, and nitric acid solution, 16:1:1 ratio) using a photoresist mask.

We then performed a second 150 μm DRIE of silicon using the patterned aluminum layer as the etch mask (Fig. 6(b)) to firm silicon via structures with larger height, i.e., the radiator, connecting via and reflectors were partially formed inside the trench. Another aluminum etch mask layer was patterned to define the shorter silicon via structure for the director at the bottom of the trench using a lift-off process of e-beam evaporated aluminum with an image reversal photoresist (AZ5214E); followed by a third 225 μm DRIE of silicon (Fig. 6(c)).

Thus, silicon vias with two different heights were formed inside the single 375 μm deep trench, which was then used as a region to accept reflowed glass. After stripping all the aluminum etch mask layers, a 0.5 μm thick tungsten layer was selectively coated on the silicon vias by sputtering using an aluminum shadow mask (Fig. 6(d)).

The resulting substrate was anodically bonded with a 4-inch, 525 μm thick borosilicate glass wafer (BOROFLOAT®33, SCHOTT AG, Mainz, Germany) in a vacuum environment (Fig. 6(e)). The shallow cavity defined by the first DRIE step ensured TGSV heights were slightly lower than the trench depth, and the tungsten layers on the TGSV top surfaces did not touch the glass wafer during anodic bonding.

Glass reflow was performed by placing the wafer stack into a furnace, heating to 800°C, holding for 8 h, and then cooling to room temperature. Thus, glass melted and flowed into the silicon trench due to lower pressure in the sealed trench compared with atmospheric pressure (Fig. 6(f)). We selected tungsten as the via coating metal layer due to its high melting point (3422°C) compared with other conductive metals, which helped to maintain the metal state during glass reflow. Both sides of the substrate were subsequently planarized by mechanically lapping and polishing using chemical mechanical polishing (Fig. 6(g)). Melted glass that overfilled the front surface was ground and carefully polished until higher TGSV surfaces were exposed; and then remaining backside silicon and glass were ground and polished until substrate thickness $= 350$ μm precisely. All TGSV surfaces were completely exposed at the wafer bottom surface.

Finally, the microstrip feedline on the top side and the feedline and ground on the backside were patterned by evaporating and patterning chromium (10 nm) and gold (300 nm)

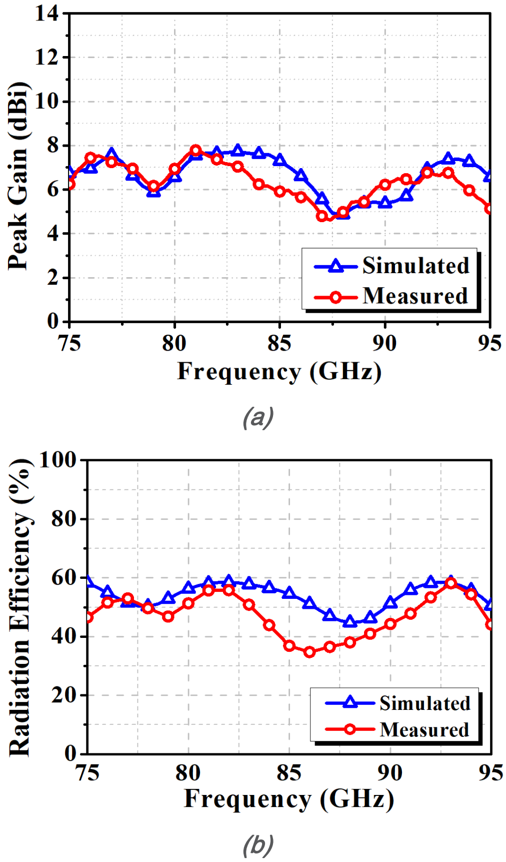

FIGURE 11. Simulated and measured (a) peak gain, and (b) radiation efficiency plot with respect to frequency.

metal layers using a lift-off process with image reversal photoresist (Fig. 6(h)).

Figs. 7(a) and (b) show the top and back sides of the fabricated prototype antenna after being diced into the sample for measurement, and the fabricated prototype was mounted on a W-band end-launch connector (Southwest Company) as shown in Fig. 7(c).

IV. MEASUREMENT RESULTS AND DISCUSSION

A. S-PARAMETER MEASUREMENTS

The S-parameters of the fabricated prototype were measured using a calibrated vector network analyzer N5260A (Keysight Technologies Corporation, Morgan Hill, CA, USA). Fig. 8 compares simulated and measured S-parameters. Measured and simulated 10 dB impedance bandwidth is 76.5–86.7 and 77.8–86.2 GHz, respectively, with measured 10 dB fractional impedance bandwidth = 12.5%. Thus, simulated and measured S-parameters are consistent.

B. RADIATION PATTERN MEASUREMENTS

Far-field radiation patterns for the fabricated prototype antenna were measured using a commercial ORBIT/FR far-field measurement system in a shielded millimeter-wave anechoic chamber, as shown in Fig. 9(a). The transmission horn antenna was SGH-series (SGH-15) by Millitech Company, with standard gain of 24 dBi.

Figs. 9(b)–(e) show measured and simulated co and cross-polarized radiation patterns at 77, 79, 81, and 83 GHz, respectively, corresponding with the 10 dB impedance bandwidth range. Measured peak gains are 7.6, 6.2, 7.8, and 7.3 dBi; whereas simulated peak gains are 7.5, 5.8, 7.7, and 7.6 dBi, respectively.

Figs. 10(a)–(d) show simulated three-dimensional radiation patterns at 77, 79, 81, and 83 GHz, respectively, with simulated and measured peak gains in Fig. 11(a). Measured radiation efficiency was calculated from the ratio of measured peak gain to simulated directivity. Measured and simulated radiation efficiency of the antenna at 77, 79, 81, and 83 GHz is 53%, 47%, 56%, and 51%; and 52%, 52%, 58%, and 58%, respectively. Fig. 11(b) shows simulated and measured radiation efficiency for the proposed antenna.

V. CONCLUSION

This paper presented a via-monopole based quasi Yagi-Uda antenna with vertical polarization in a planar configuration for W-band applications on ultrathin (350 μm) borosilicate glass substrates using a tungsten coated TGSV process. Measured performance exhibited good preliminary results with 10 dB fractional bandwidth of 12.5% and a measured gain of 7.8 dBi at 81 GHz within the 10 dB impedance bandwidth for the W-band. Simulated and measured results exhibit good agreement. The proposed antenna confirms the feasibility of glass interposers with TGVs and will provide a useful baseline for developing fully integrated millimeter-wave systems. The wafer level batch processing microfabrication technology will also play an important role for developing RF circuits and components in the W-band or higher frequencies, enabling high data rates on ultra-thin glass substrates.

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