Cavity-backed Antennas using Quartz Glass on Silicon Hybrid Bonded Wafers for Sub-THz Communication and Radar Applications

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Abstract

In this work, we present a novel cavity-backed wideband and high gain antenna using Quartz glass and silicon bonded wafers for sub-THz wireless communication and radar sensing applications. We rigorously studied the impact of the dimensions of the cavity on the gain, bandwidth and radiation pattern of the antenna. Test samples of the antenna were fabricated and measured. Excellent correlation was obtained between measurement and simulation results. For optimal cavity dimensions, maximum gain per patch element of approximately 7 dBi and bandwidth of 14 GHz were obtained.

Key words

antenna array, cavity backed antenna, sub-THz Radar, Bonded wafer, Quartz glass

I. Introduction

In recent years, the sub-THz bands have received much research attention, because they offer enormous continuous bandwidth. Bandwidth plays a significant role in wireless systems. The larger the bandwidth the higher the range resolution of radar systems and the higher channel capacity in communication systems. Consequently, sub-THz bands, especially the D-band, are currently being explored for future 6G communication [1] and automotive radar systems [2].

However, the development of wireless systems at sub-THz bands is quite challenging, partly because of very high intra- and inter-system losses at these frequencies. One of the key system components used to overcome inter-system losses are antennas. The efficiency (and hence, gain) of an antenna is dependent on the dielectric losses. Therefore, one way to improve the antenna gain (without increasing the antenna aperture) is to use low-loss dielectrics. If low-loss dielectrics are also used to fabricate transmission lines that interconnect sub-THz frontend components on the package, then intra-system losses can also be reduced. Increasing the antenna gain and reducing the interconnect losses between the antennas and the power amplifiers significantly improves the equivalent isotropic radiated power (EIRP), for the same output power of the power amplifiers. Such an increase in EIRP also helps to overcome the inter-system losses caused by free-space loss and atmospheric conditions. Therefore, by using low-loss materials, both intra- and inter-system losses can be reduced, leading to an increase of performance and energy efficiency of sub-THz systems. Furthermore, the communication and detection ranges of sub-THz communication and radar systems can be greatly improved. Hence, low loss materials play a key role in the development of sub-THz wireless systems.

Typically, ceramic-filled PTFE based low-loss dielectric materials are used for the development of antennas for very high frequency applications. One example of such a material is RO3003TM laminates, with relative dielectric constant (Dk) of 3 and loss tangent (Df) of 0.001 (at 10 GHz) [3]. However, there are two main issues concerning such PTFE-based laminates: 1) The process variations which occur during the fabrication of antennas on these laminates have significant impact on the antenna parameters. Due to the high sensitivity of sub-THz components to geometrical tolerances these variations may shift the operating frequencies of the antenna completely out of the desired band; 2) These materials contain PFAS. Due to the long-term harmful nature of PFAS to humans and environment, a ban on PFAS is currently being considered in the EU [4] and other parts of the world. Hence, alternative low Dk and low Df materials are required.

One alternative material is Quartz glass. Quartz glass offers lower losses (i.e., has smaller Df) than PTFE-based materials, although it has higher Dk. Furthermore, process variations which occur during the fabrication of antennas on Quartz glass are very small and cause less impact on the antenna performance. The smooth glass surface leads to a reduction of the roughness of the metallization decreasing metal loss.

Due these excellent characteristics, Quartz glass has been used for the development of sub-THz antennas, e.g. [5]. However, the bandwidth of these antennas is less than 10 GHz. To fully explore the bandwidth advantages offered by the sub-THz band, wideband antennas that can cover larger bandwidths are required. As Quartz glass cannot be directly used in a standard PCB technology advanced packaging and process technologies are required for integration into sub-THz wireless systems.

In this work, we present a novel cavity-backed wideband and high gain antenna on bonded Quartz glass and silicon wafers for sub-THz applications. The introduction of the air cavity causes a reduction in the effective Dk value, and thus leads to an increase in the bandwidth. To improve the impedance matching, the antenna is fed by a quarter-wavelength transmission line. Furthermore, we rigorously studied the impact of the dimensions of the cavity on the gain, bandwidth and radiation pattern of the antenna. Test samples of the antenna were fabricated and measured. Excellent correlation was obtained between measurement and simulation results. Depending on the dimensions of the cavity, maximum gain per patch element of approximately 7 dBi and bandwidth of 14 GHz were achieved.

The remaining sections of this paper are structured as follows: In section II, the stack-up of the novel quartz-glass bonded wafer antenna is briefly presented. The modeling and simulation results, considering the impact of the dimensions of the cavity on the antenna are presented in section III. Finally in section IV, fabricated samples as well as measurement results are shown.

II. STACK-UP OF CAVITY-BACKED ANTENNA ON BONDED QUARTZ GLASS AND SILICON WAFERS

Fig. 1 shows the stack-up (side view) of the novel cavity-backed, wideband and high gain antenna on bonded quartz glass and silicon wafers.

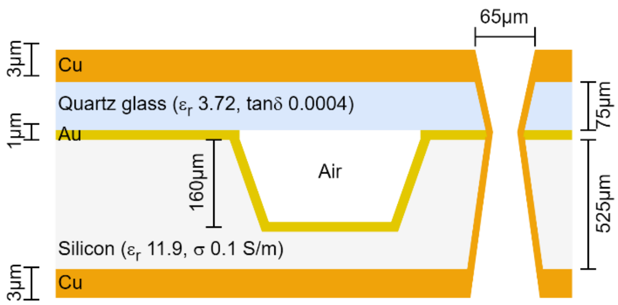


Fig. 1 Stack up of novel cavity-backed, wideband and high gain antenna on bonded quartz glass and silicon wafers.

The Quartz glass has a Dk of 3.72 and Df of 0.0004, while silicon has Dk of 11.9, and conductivity of 0.1 S/m. At the top and bottom of the stack-up are Cu metal layers while an Au layer is located at the interface between quartz glass and silicon. An air-filled cavity with metallized walls is formed at the interface between silicon and quartz glass layers. The metal layers on top of the quartz glass layer and the silicon layer are used for the design of the antenna. Through glass vias connecting the top metal layer with interface Au layer, while through silicon vias can be used to connect the Au metallization layer with the bottom Cu layer.

III. MODELLING AND SIMULATIONS OF GLASS BASED ANTENNAS USING BONDED WAFER SUBSTRATE

To explore the technological capability of utilizing cavities to decrease effective permittivity, a study was conducted to assess the influence of cavity dimensions. Various cavity depths and widths were employed to achieve the target frequency of 140 GHz. For each parameter, adjustments were made to the top metallization of the actual patch and the quarter-wave line segment to maintain the center frequency.

Fig. 2 illustrates the configuration of this study. A rectangular patch was positioned on a quartz layer above the silicon layer. Centrally located beneath the patch is a rectangular air cavity within the silicon layer, featuring sidewall angles of 80 degrees. The depth of the cavity was varied between 100 and 400 µm, while the width and length were maintained at 1000 and 790µm. The length of the quarter wave transformer was set to 277µm with varying width. The patch length was set to 490µm as radiator without cavity and varied between 546 and 573µm for different cavity depths between 100 and 400µm.

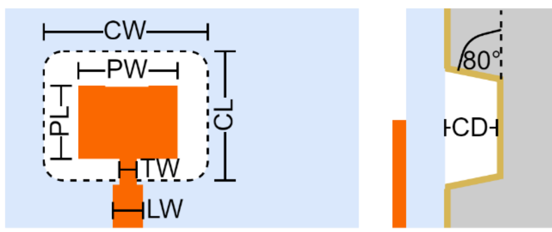


Fig. 2 Top and side views of the antenna element. Abbreviations: CD: cavity depths, CL: cavity length, CW: cavity width, LW: line width, PL: patch length, PW: patch width, TW: transformer width

In order to compare the results, the width TW of the quarter-wave line and the length PL of the patch were modified to match and align with the target frequency of 140 GHz (cf. Fig. 3).

The significant enhancement of the 10 dB bandwidth is evident with the introduction of deeper cavities, leading to an almost twofold increase in bandwidth within the studied range (see Fig. 6).

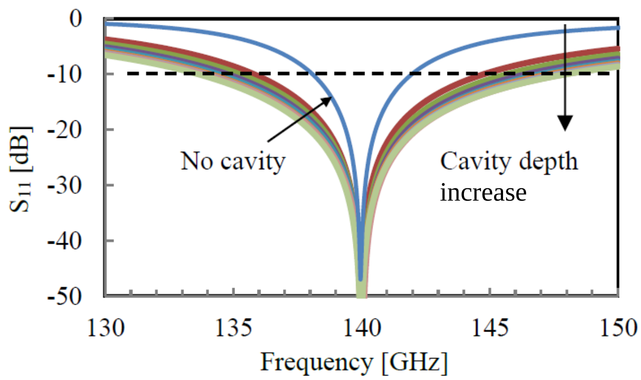


Fig. 3 Return loss simulation results for structure in Fig. 2. Blue curve: without cavity, others: cavity depth from 100 to 400µm.

Compared to a conventional patch the radiation pattern exhibits a slight broadening, resulting in a diminished gain at boresight (cf. Fig. 4). While this modification in radiation characteristics shows a minor effect, the primary impact of the air-filled cavity is the significant increase in bandwidth.

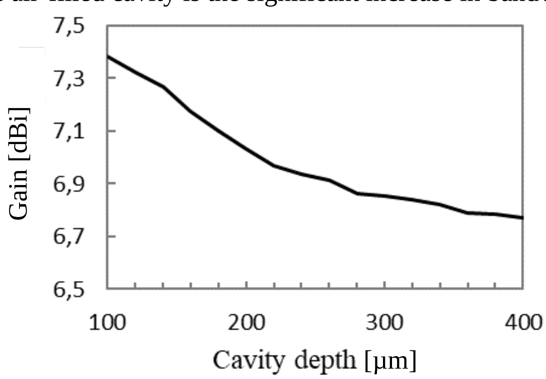


Fig. 4 Simulation results of the obtained gain of the single antenna elements with varying cavity depths. The corresponding gain of the radiator without cavity was simulated to be around 7.5 dBi.

Simulation results examining a range of cavity dimensions, including circular cavities with a radius of 1000µm, consistently reveal that larger cavity sizes—whether in terms of depth, width, or radius—lead to enhanced bandwidth. This behavior is evident across various cavity configurations.

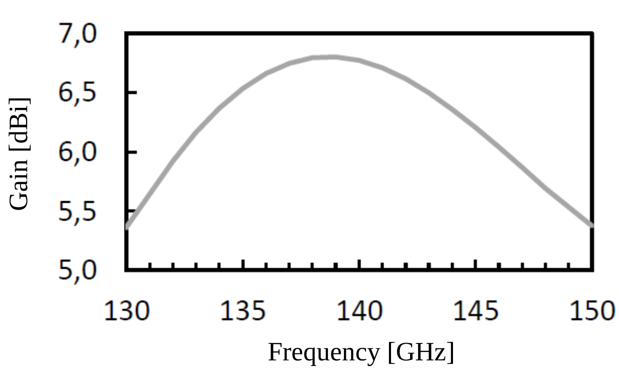


Fig. 5 Simulation results of gain for cavity depth 165µm.

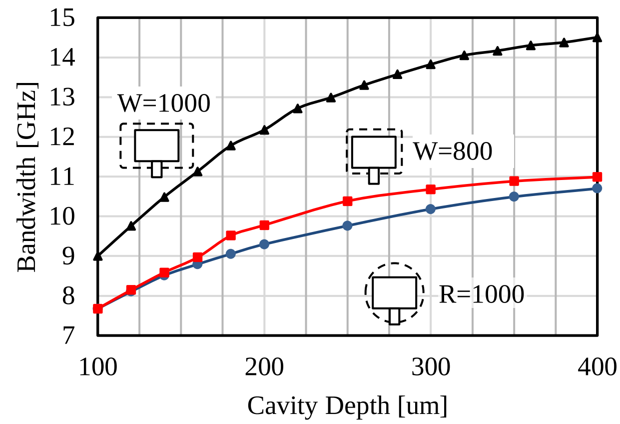
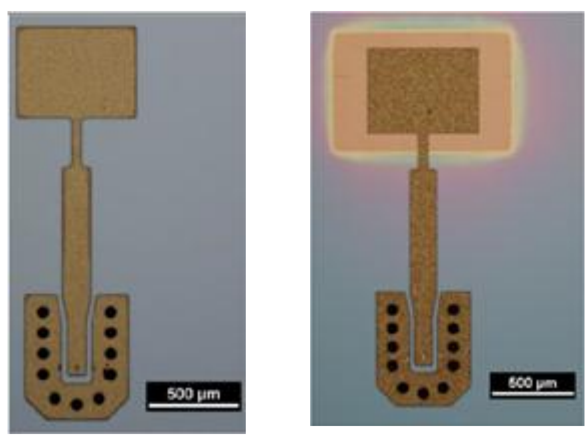


Fig. 6 Simulation results of 10 dB bandwidth for different cavity sizes and shapes. Blue: circular cavity, red and black: rectangular cavity

IV. FABRICATION, MEASUREMENT AND VERIFICATION

Following the design procedure from the previous section, various antenna designs were been fabricated. Each variant was designed with and without air-filled cavity with a depth of 160µm. Fig. 7 shows examples of the fabricated test samples. The copper thickness of the top quartz layer has a thickness of roughly 4 microns, corresponding to more than 10 times the skin depth at 140 GHz. The top surface of the silicon was gold plated with 2 microns, surrounding the cavity walls with solid conductance.



Patch antenna with transmission line transformer

Cavity-backed patch antenna with transmission line transformer

Fig. 7 Photos of fabricated antennas

S-parameter measurements were performed using a vector network analyzer (Keysight PNA-X N5290A) with external frequency extension modules (VDI WR6.5 -VNAX) on a manual wafer probe station (Formfactor Summit 11000). The test structures were contacted using waveguide RF probes (Formfactor Infinity i170-T-GSG-100-BT) mounted to the

frequency extension modules.
Fig. 8 shows the comparison of the simulation and measurement results, as an example. As can be seen, excellent correlation was obtained between measurement and simulation results.

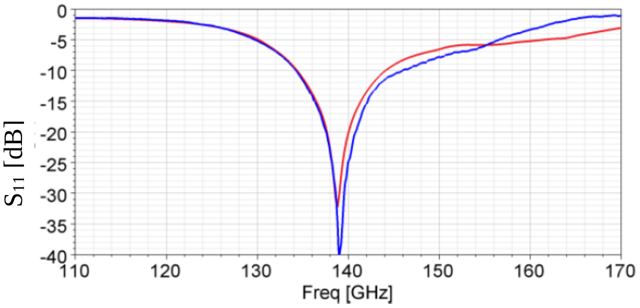


Fig. 8 Comparison of simulated (red) and measured (blue) reflection coefficient for cavity backed inset feed patch antenna

In Fig. 9, the return loss for transmission line transformer patch antennas with and without cavity. The obtained bandwidth were 17.3 GHz and 4.4 GHz respectively for the antenna with and without the cavity.

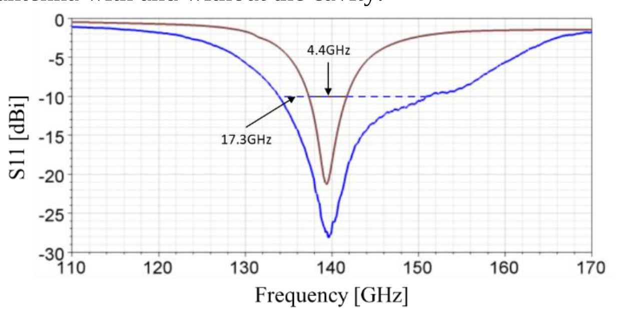


Fig. 9 Comparison of measured bandwidth for transmission line transformer patch antenna with (blue) / without (brown) cavity

Radiation pattern measurements were performed using an automated spherical far-field measurement set-up (NSI MI 7000-360) and a Keysight PNA N5227A vector network analyzer with frequency extension modules (VDI WR6.5-VNAX). The test structures were contacted using RF probes (Formfactor Infinity i170-T-GSG-100-BT) (cf. Fig. 10).

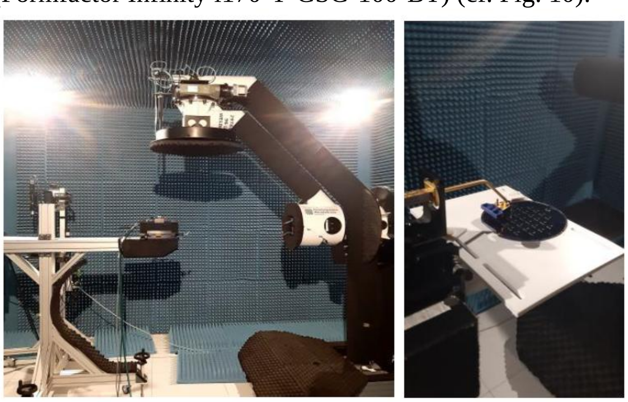


Fig. 10 Spherical far-field measurement system used for radiation pattern measurements

The antenna measurement system consists of a scanner with a reference horn antenna and a stand with a support for the AUT.

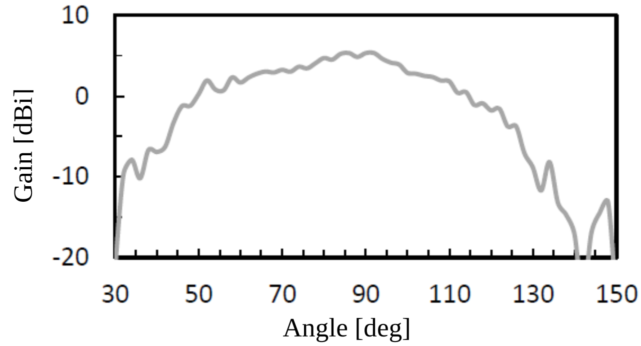


Fig. 11 H-plane radiation pattern measurement of transmission line transformer cavity backed patch antenna

The antenna radiation pattern measurement results show beamwidth and gain comparable to a standard patch antenna in the H-plane (cf. Fig. 11). Results for E-plane measurements are comparable.

V. Conclusion

The design of novel cavity-backed wideband antennas operating at 140 GHz using a Quartz-glass and Silicon bonded-wafer has been investigated. The bandwidth of the cavity-backed antenna could be increased from 4.4 GHz to 17.3 GHz compared to an antenna without cavity. The novel antenna achieves a maximum gain of approximately 7 dBi, with a cavity depth of 165 µm. The gain depends on the cavity depth.

It is planned to extend the investigations to arrays to increase the antenna gain and thus reduce the impact of high free-space path loss for D-band radio applications.

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