Research Article

A Cylindrical Dielectric Resonator Antenna-Coupled Sensor Configuration for 94 GHz Detection

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Received 22 October 2013; Revised 13 February 2014; Accepted 13 February 2014; Published 17 March 2014

Academic Editor: Ahmed A. Kishk

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A novel antenna-coupled sensor configuration for millimeter wave detection is presented. The antenna is based on two cylindrical dielectric resonators (CDRs) excited by rectangular slots placed below the CDRs. The $\text{HEM}_{11\Delta}$ mode resonating at 94 GHz is generated within the CDRs and a 3 GHz impedance bandwidth is achieved at center frequency of 94 GHz. The simulated antenna gain is 7.8 dB, with a radiation efficiency of about 40%.

1. Introduction

Antennas coupled with sensors such as microbolometers [1–5], metal-insulator metal (MIM) diodes [6, 7] have been investigated for imaging and spectroscopy applications in the millimeter wave (MMW) and terahertz (THz) spectral regions. In antenna-coupled microbolometers, the antenna resonant current flows in the microbolometer located at the feed of the antenna causing joule heating in the microbolometer element. This joule heating translates into a resistance change of the microbolometer. The resistance change is sensed by biasing the microbolometer element with a constant current and monitoring the voltage change resulting from the incident radiation. Whilst in antenna-coupled MIM and Schottky diodes the detection mechanism is such that antenna resonant currents are being rectified by the diode located at the feed of the antenna leading to a resultant dc current component.

Dielectric resonator antennas (DRAs) operating in the MMW band possess many merits that make them preferable in antenna-coupled sensor configurations. DRAs, operating in the MMW band, have shown high radiation efficiencies

as compared to printed metallic antennas. This is mainly due to the absence of conductor and surface wave losses which are greatly dominant in printed metallic antennas. In addition, DRAs have different shapes with many possible excitation modes and feeding schemes which imply great design flexibilities [8, 9]. Moreover, recent developments in low dielectric permittivity polymer-based DRAs operating in the *K*-band [10] have shown good antenna efficiencies and fabrication simplicity. All of the previously mentioned DRAs qualities in addition to the ongoing developments, at Prince Sultan Advanced Technologies Research Institute (PSATRI), for photolithographically patternable polymer-ceramic composites with dimensions commensurate with MMW *W*-band DRAs, have led to the development of the DRA-coupled sensor configuration presented in this work.

In this paper we present a novel antenna-coupled sensor configuration for 94 GHz detection. We present a coplanar waveguide (CPW) fed slot-coupled cylindrical DRA (CDRA). The antenna is based on two cylindrical dielectric resonators (CDRs) excited by means of rectangular slots placed below the CDRs; the $\text{HEM}_{11\Delta}$ mode resonating at 94 GHz is generated within the CDRs. CPWs are used to feed

the antenna resonant currents to the sensor which is placed at the center of the CPW. Direct current (dc) cuts are introduced in the top ground plane to allow for sensor bias and detected signal readout. Simulation results show that the antenna gain can reach 7.8 dB, with a beam width of approximately 60° in XZ plane ($\theta = 0^\circ$, $\varphi = 0^\circ$) and approximately 20° YZ plane ($\theta = 0^\circ$, $\varphi = 90^\circ$). The antenna radiation efficiency can reach 40%.

2. Antenna Design and Configuration

The 3D model of the proposed antenna structure is illustrated in Figure 1. The antenna consists of a quartz substrate sandwiched between two thin aluminum layers. The 50 Ω lumped port functions as a feeding scheme and is placed between the two CPW conductors, such feeding scheme along with the dc cuts split the top ground plane into two equal and electrically isolated parts which allow for dc biasing the sensor. The two CDRs are placed over the top aluminum layer and excited by means of rectangular slots coupled with CPW lines on the top aluminum layer.

The resonance frequency (f_0) for CDR can be calculated as follows [11]:

$$k_0 a = \frac{2\pi f_0 a}{c} = \frac{6.324}{\sqrt{\epsilon_r + 2}} \times \left[0.27 + 0.36 \left(\frac{a}{2H} \right) + 0.02 \left(\frac{a}{2H} \right)^2 \right], \quad (1)$$

where k_0 is the free space wavenumber, c is the speed of light in vacuum, ϵ_r is dielectric constant of DR, and a and H are the radius and height of CDR, respectively.

For W band applications, the dimensions of cylindrical dielectric resonator having $\epsilon_r = 4$ are found to be D_r (radius) = 1.41 mm and D_h (height) = 350 μm , resulting in HEM_{11 Δ} mode at 94 GHz. The side view (YZ-plane) of antenna structure is shown in Figure 2. Initially, the center to center distance between the CDRs is kept at $C = \lambda_0$ where λ_0 is free space wavelength at 94 GHz. The quartz substrate has thickness of $th_{\text{sub}} = 300 \mu\text{m}$ with $\epsilon_r = 3.78$. The thickness of aluminum layers is chosen to be $th_{\text{alu}} = 0.22 \mu\text{m}$.

Various design parameters are illustrated in the top view (XY-plane) as shown in Figure 3. Initially, the quartz substrate having length $L_1 = 14 \text{ mm}$ and width $W_1 = 10 \text{ mm}$ is fully covered with aluminum at the top and bottom. Two narrow slots are placed at the center of CDR which are made to excite HEM_{11 Δ} mode within the CDRs. Initially, the center of rectangular excitation slot is aligned with the center of CDR; that is, $S_{\text{off}} = 0 \text{ mm}$. The excitation slot is coupled to the CPW feed network. A 50 Ω lumped port is placed at the middle of CPW.

The red dotted area in Figure 3 is zoomed and shown in Figure 4 for a more detailed view of excitation slot, CPW feeding lines, and bolometer resistor placement. The CPW line is divided into two equal parts by introducing a gap of $P_w = 0.01 \text{ mm}$ for bolometer resistor placement. For simulation purpose a lumped port having impedance of 50 Ω

FIGURE 1: 3D model of proposed CDRA structure.

FIGURE 2: Side view of proposed antenna geometry (YZ plane), with $th_{\text{sub}} = 0.22 \mu\text{m}$, $th_{\text{cdr}} = 300 \mu\text{m}$, $D_h = 0.35 \text{ mm}$, $D_r = 1.41 \text{ mm}$, and $C = 3.19 \text{ mm}$.

FIGURE 3: Top view of proposed antenna geometry (XY plane), with $L_1 = 14 \text{ mm}$, $W_1 = 10 \text{ mm}$, $L_2 = 11.68 \text{ mm}$, $W_2 = 5.82 \text{ mm}$, $S_{\text{off}} = 0 \text{ mm}$, $C_L = 1 \text{ mm}$, and $C_{\text{th}} = 13 \mu\text{m}$.

FIGURE 4: Top view of proposed antenna geometry (XY plane), with $W = 0.19 \text{ mm}$, $G = 20 \mu\text{m}$, $L_s = 0.55 \text{ mm}$, $W_s = 0.11 \text{ mm}$, $L_{\text{stub}} = 0.5 \text{ mm}$, $C_{\text{off}} = 0.15 \text{ mm}$, and $P_w = 0.01 \text{ mm}$.

is placed between the two CPW lines. For the CPW in a $50\ \Omega$ system placed over a quartz substrate, the conductor width and air gap width are taken to be $W = 0.19\text{ mm}$ and $G = 0.02\text{ mm}$, respectively. Initially, the length of rectangular excitation slot for CDRs is found by $L_s = 0.4\lambda_0/\sqrt{\epsilon_e}$, where ϵ_e is effective dielectric constant; that is, $\epsilon_e = \sqrt{\epsilon_{\text{sub}}^2 + \epsilon_{\text{cdr}}^2}$. ϵ_{sub} and ϵ_{cdr} are dielectric constants of the substrate and CDR, respectively, whereas the width of excitation slot is chosen by $W_s = 0.2L_s$. Initially, excitation slot is placed exactly at the center of CDR. The stub extension L_{stub} is chosen by $L_{\text{stub}} = \lambda_g/4$, where λ_g is the guided wavelength is substrate at 94 GHz.

3. Simulation and Optimization

The CDRA structure presented in Section 2 is simulated and optimized using Ansys HFSS. To improve the coupling between the excitation slot and CDR an offset distance between the center of CDR and center of excitation slot is introduced. The optimized offset position of the center of excitation slot is found to be $S_{\text{off}} = 0.06\text{ mm}$ from the center of CDR. Initially, the top aluminum layer was also fully covered with aluminum; during the optimization process we found that the main to side lobe ratio in antenna radiation pattern is highly influenced by the dimensions of length (L_2) and width (W_2) of top aluminum ground plane; by optimizing the dimensions of top aluminum ground plane a difference of approximately 10 dB between the main and first side lobe is achieved. The optimized dimensions for the top aluminum layer are found to be length $L_1 = 11.68\text{ mm}$ and width $W_1 = 5.82\text{ mm}$. To make this antenna suitable for antenna-coupled bolometer applications, various schemes for the DC cuts, that is, straight horizontal, straight vertical, diagonal, and staircase, were studied to split the top aluminum layer into two electrical isolated parts as shown in Figure 5. The staircase DC cuts are found to be the most effective and suitable for proposed antenna structure. The optimized dimensions related to DC cuts are thickness $C_{\text{th}} = 0.13\text{ mm}$, length of $C_L = 1\text{ mm}$, and offset of $C_{\text{off}} = 0.16\text{ mm}$ from the top of excitation slot.

A comparison between the initial design values and final optimized values is shown in Table 1.

The antenna return loss is illustrated in Figure 6. The antenna bandwidth is found to be 3.8 GHz, that is, (92.5–96.3 GHz). To validate the proper excitation and resonance of CDRA, The dielectric resonators from the antenna structure are removed and simulation is carried out; the S_{11} for this case is shown in the inset of Figure 5.

The antenna radiation pattern in YZ plane ($\theta = 0^\circ$, $\varphi = 0^\circ$) at 94 GHz is illustrated in Figure 7(a). As shown in the figure a broad and symmetric radiation pattern is achieved having maximum gain of 7.8 dB at center frequency of 94 GHz. The 3 dB beam width is found to be approximately 60° ; furthermore, the antenna front to back ratio of 27 dB is achieved. As illustrated in Figure 7(b), the antenna radiation pattern in XZ plane ($\theta = 0^\circ$, $\varphi = 90^\circ$) is narrow and symmetric. The 3 dB beam width is found to be approximately 14° with main to side lobe level at 9 dB. The peak realized gain and

FIGURE 5: DC cut for top aluminum layer. (a) Straight horizontal, (b) straight vertical, (c) diagonal, and (d) staircase.

antenna efficiency are shown in Figure 8. The peak realized gain of proposed antenna remains above 5.5 dB for the whole frequency band of operation whereas the antenna efficiency is found to be approximately 40% throughout the band of interest. The E field distribution on top aluminum layer is shown in Figure 9.

4. Conclusion

The investigation in this paper enables exploring the benefits arising from coupling microbolometers, diodes, and other

FIGURE 6: Antenna return loss (S_{11}), with $L_1 = 14$ mm, $W_1 = 10$ mm, $L_2 = 11.68$ mm, $W_2 = 5.82$ mm, $S_{\text{off}} = 0.06$ mm, $C_L = 1$ mm, $C_{\text{th}} = 13 \mu\text{m}$, $W = 0.19$ mm, $G = 20 \mu\text{m}$, $L_s = 0.75$ mm, $W_s = 0.103$ mm, $L_{\text{stub}} = 0.417$ mm, $C_{\text{off}} = 0.16$ mm, and $P_w = 0.01$ mm.

TABLE 1: Comparison of initial and final optimized design parameter.

Antenna parameter	Initial value (mm)	Optimized value (mm)
C	3.19	3.86
L_2	14	11.68
W_2	10	5.82
S_{off}	0	0.06
L_s	0.55	0.75
W_s	0.11	0.103
L_{stub}	0.5	0.417
G	0.02	0.02
W	0.19	0.19
C_{off}	0	0.16
C_{th}	0.01	0.013

sensors to DRAs and similar high gain single ended antenna structures at millimeter wave and terahertz frequencies. Microbolometers and diodes require differential feed for signal bias and readout and so were prohibited from being coupled to regular common DRA designs. The presented design explored a novel antenna-coupled microbolometer configuration. The antenna top aluminum layer is divided into two electrically isolated parts by utilizing staircase DC cuts, CPW line, and a bolometer resistor. The DR having $\epsilon_r = 4$ is utilized in this design, and $\text{HEM}_{11\Delta}$ mode is excited within the DR by means of rectangular slot placed at a offset of 0.06 mm from the center of DR. The quartz having $\epsilon_r = 3.78$ and aluminum is used for substrate and conducting parts in the antenna structure, respectively. The impedance bandwidth of 3.8 GHz is achieved at center frequency of 94 GHz with a very reasonable gain of above 7 dB throughout the whole band of operation. The antenna efficiency is found to be 40%.

(a) YZ plane

(b) XZ plane

FIGURE 7: Simulated radiation pattern at 94 GHz. (a) YZ plane, (b) XZ plane, with $L_1 = 14$ mm, $W_1 = 10$ mm, $L_2 = 11.68$ mm, $W_2 = 5.82$ mm, $S_{\text{off}} = 0.06$ mm, $C_L = 1$ mm, $C_{\text{th}} = 13 \mu\text{m}$, $W = 0.19$ mm, $G = 20 \mu\text{m}$, $L_s = 0.75$ mm, $W_s = 0.103$ mm, $L_{\text{stub}} = 0.417$ mm, $C_{\text{off}} = 0.16$ mm, and $P_w = 0.01$ mm.

Conflict of Interests

There is no conflict of interests with any party regarding the submitted manuscript.

Acknowledgment

This work was supported by the Annual Grants Program at King Abdulaziz City for Science and Technology (KACST) under Grant AT-4-13.

FIGURE 8: Antenna gain and efficiency, with $L_1 = 14$ mm, $W_1 = 10$ mm, $L_2 = 11.68$ mm, $W_2 = 5.82$ mm, $S_{\text{off}} = 0.06$ mm, $C_L = 1$ mm, $C_{\text{th}} = 13$ μm , $W = 0.19$ mm, $G = 20$ μm , $L_s = 0.75$ mm, $W_s = 0.103$ mm, $L_{\text{stub}} = 0.417$ mm, $C_{\text{off}} = 0.16$ mm, and $P_w = 0.01$ mm.

FIGURE 9: E -field distribution on top aluminum layer with $L_1 = 14$ mm, $W_1 = 10$ mm, $L_2 = 11.68$ mm, $W_2 = 5.82$ mm, $S_{\text{off}} = 0.06$ mm, $C_L = 1$ mm, $C_{\text{th}} = 13$ μm , $W = 0.19$ mm, $G = 20$ μm , $L_s = 0.75$ mm, $W_s = 0.103$ mm, $L_{\text{stub}} = 0.417$ mm, $C_{\text{off}} = 0.16$ mm, and $P_w = 0.01$ mm.

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