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Research Article

A DR Loaded Substrate Integrated Waveguide Antenna for 60 GHz High Speed Wireless Communication Systems

Nadeem Ashraf, Hamsakutty Vettikalladi, and Majeed A. S. Alkanhal

Electrical Engineering Department, College of Engineering, King Saud University, P.O. Box 800, Riyadh 11421, Saudi Arabia

Correspondence should be addressed to Hamsakutty Vettikalladi; hvettikalladi@ksu.edu.sa

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The concept of substrate integrated waveguide (SIW) technology along with dielectric resonators (DR) is used to design antenna/array for 60 GHz communication systems. SIW is created in the substrate of RT/duroid 5880 having relative permittivity $\varepsilon_r = 2.23$ and loss tangent $\tan\delta = 0.003$. H-shaped longitudinal slot is engraved at the top metal layer of the substrate. Two pieces of the DR are placed on the slot without any air gap. The antenna structures are modeled using CST Microwave Studio and then the results are verified using another simulation software HFSS. Simulation results of the two designs are presented; first a single antenna element and then to enhance the gain of the system a broadside array of 1×4 is presented in the second design. For the single antenna element, the impedance bandwidth is 10.33% having a gain up to 5.5 dBi. Whereas in an array of 1×4 elements, the impedance bandwidth is found to be 10.70% with a gain up to 11.20 dBi. For the single antenna element and 1×4 antenna array, the simulated radiation efficiency is found to be 81% and 78%, respectively.

1. Introduction

The demand for wireless gadgets has been increasing rapidly in the society and most of their applications are related to streaming of high definition multimedia contents. Therefore, the need for utilization of a frequency band that can provide large bandwidth that will be sufficient for all the current and future bandwidth hungry services is evident. For the past few years, the researchers have been showing deep interest in 60 GHz (V-band) of millimeter wave frequency band. The reason is its unique spectral characteristics. An interesting and significant phenomenon at this frequency band is the oxygen absorption that results in atmospheric attenuation of 10–15 dB/km. Because of this phenomenon, the worldwide 7 GHz continuous unlicensed frequency band (59–66 GHz) is the most suitable option for wireless local area networks (WLAN), wireless personal area networks (WPAN), and body area networks (BAN) communications [1]. High level of atmospheric attenuation results in the reduction of cochannel interference and the risk of signal interception that makes 60 GHz frequency spectrum a natural candidate for short range communication purpose [2, 3]. The national and international regulatory bodies have been working to set the standards for this frequency band and most of the standards have been finalized and drafted [4].

Antenna is the most fundamental element in wireless communication systems. Research communities are trying to produce efficient antenna systems for 60 GHz frequency band. The conventional technology approaches of antenna designing, for example, microstrip, striplines, or coplanar waveguides may result in spurious radiation and high level of ohmic losses in circuit designs at this frequency band. Therefore, waveguides are one of the best alternatives for millimeter wave circuit designs as they have the capability of high power handling and low losses. Fabricating such waveguides within the substrate with solid walls cannot be realized. Therefore, a new generation of high frequency integrated circuits named substrate integrated waveguides (SIW) was introduced [5, 6]. SIW is a transition between microstrip and waveguide design structures. The upper and lower metal layers of a substrate are made short circuit through metalized via holes. The structure is excited through a matched microstrip feeding lines and connected with SIW through a transition [7]. The authors have presented different antenna configurations for large bandwidth and high gain at 60 GHz communications [8–11]. Many antenna designs are proposed for this frequency

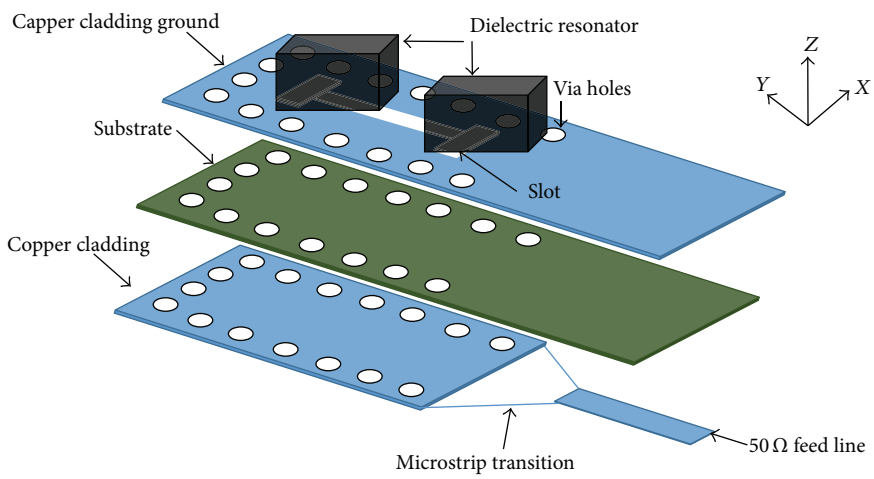


Figure 1: SIW single antenna element 3D exploded model view.

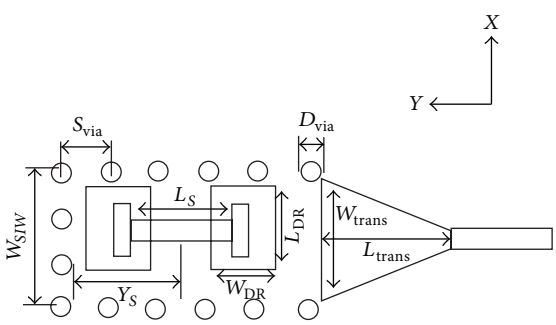


Figure 2: SIW antenna design parameters (top view).

band in which the wide bandwidth is achieved by using either the multilayer techniques or with the substrate having large thickness. However, large thickness results in the increase of dielectric losses. Therefore the concept of SIW technology within a thin substrate is proposed to avoid this problem. Loading the antenna design structure with DR has been proposed by many researchers to achieve wide bandwidth, low losses, and ease of fabrication. Along with the material properties of the DR, the shape and aspect ratio of the DR also play an important role in antenna bandwidth enhancement and radiation characteristics. Recently, a novel design of supershaped dielectric resonator antennas (S-DRAs) for wide band applications is proposed in [12], where different S-DRAs configurations have been proposed and experimentally verified. The antenna design is proposed by combining supershaped based cylindrical geometry and plastic manufacturing material. The polarization analysis is also performed and linear as well as circular polarization designs are proposed.

In this paper, the authors are presenting SIW based single antenna element and then a 1 × 4 broadside array to achieve desired high gain. The fundamental structure consists of a thin RT/duroid 5880 substrate in which the H-shape longitudinal slot is engraved at the ground metal layer and two pieces of dielectric resonators (DR) of the same material with larger thickness of 0.79 mm are placed over the fundamental structure. This fundamental structure acts as a source to resonate the DR at matching frequency band to achieve large bandwidth. More than 6 GHz bandwidth is achieved in the proposed antenna/array designs. The total bandwidth is a cumulative effect of two types of resonances, one from the long section of longitudinal slot and the other is from the modes of rectangular DR that are excited by the small apertures designed at both ends of the slot.

2. Antenna Design

2.1. SIW Single Antenna Element. The 3D model view of SIW single antenna element is shown in Figure 1. The design consists of a single substrate with two pieces of DR. A low-cost/loss substrate material RT/duroid 5880 having permittivity $\varepsilon_r = 2.23$ and loss tangent $\tan\delta = 0.003$ with thickness 0.127 mm and copper cladding thickness 0.0175 mm is used. The metalized via holes are designed to create SIW. The metal used for cladding and via holes is copper with a conductivity of $\sigma = 5.8 \times 10^7$ s/m.

The SIW design parameters are calculated by following the rules provided in the literature [13]. In Figure 2, the SIW parameters are defined. SIW width (W_{SIW}) is the center to center distance of via holes creating sidewalls of the SIW, D_{via} is the diameter, and S_{via} is the center-to-center distance between two consecutive via holes. The length and wall-to-wall width of SIW antenna element is 10 mm and 1.9 mm, respectively. A 50 Ω microstrip line is used for feeding the structure, which is connected to SIW through a microstrip to waveguide transition having width W_{trans} and length L_{trans} [7]. The width of 50 Ω microstrip line is 0.38 mm. A longitudinal H-shape slot is engraved at the ground plane, having width W_s length L_s and displacement from the symmetry axis is X_s. One end of the SIW is made short circuit to produce standing waves inside SIW. The distance from the short circuit end to the middle of the slot is Y_s. The standing waves will be radiated through the H-shape aperture engraved at the ground plane. The optimized results were obtained with $L_s \approx \lambda_0/2$ and $Y_s = 3\lambda_0/4$ as slot parameters, where λ_0 is

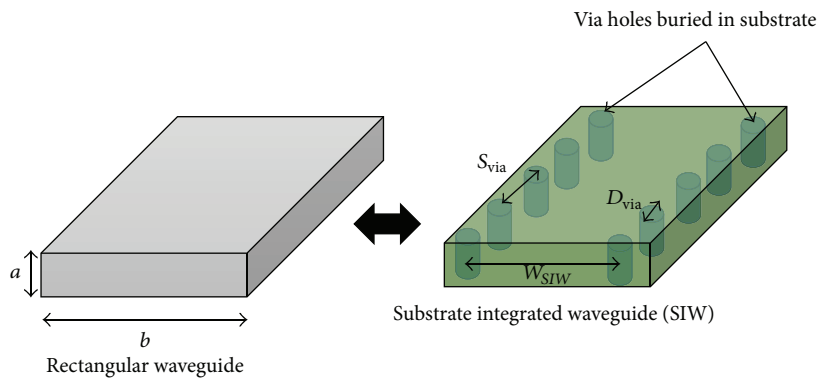


Figure 3: SIW equivalent rectangular waveguide.

the guided free space wavelength at 60 GHz. The optimized width and length of side arms of the H-shape slot are 0.60 mm each, that is, approximately $\lambda_0/8$.

The SIW parameters are designed according to the guidelines provided by Yan et al. in [13] and the procedure to find equivalent rectangular waveguide is shown in (1)–(5). Therefore, the analytical design confirmation is performed for proposed SIW equivalent rectangular waveguide with dielectric permittivity $\varepsilon_r = 2.23$ and 60 GHz frequency of operation. For the dominant mode (TE_{10}) propagation, SIW with its width $W_{SIW} = 2.4$ mm is needed to design that is equivalent to the dielectric filled rectangular waveguide having width $b = 2$ mm. This design will have only the dominant mode propagation with cutoff frequency of 50.2 GHz. Consider

$$X = x_1 + \frac{x_2}{S_{via}/D_{via} + (x_1 + x_2 - x_3)/(x_3 - x_1)}, \quad X = 0.827, \tag{1}$$

where the constants x_1, x_2, and x_3 are defined in (2)–(4) and their numerical values are calculated. Consider

$$x_1 = 1.0198 + \frac{0.3465}{W_{SIW}/S_{via} - 1.0684}, \quad x_1 = 1.138, \tag{2}$$

$$x_2 = -0.1183 - \frac{1.2729}{W_{SIW}/S_{via} - 1.2010}, \quad x_2 = -0.573, \tag{3}$$

$$x_3 = 1.0082 - \frac{0.9163}{W_{SIW}/S_{via} + 0.2152}, \quad x_3 = 0.79. \tag{4}$$

The width "b" of equivalent rectangular waveguide and the width of SIW "W_{SIW}" are related to each other as given in (5). The SIW equivalent rectangular waveguide is illustrated below in Figure 3. The constant "X" is calculated using (1) and it is used in (5) to calculate SIW equivalent rectangular waveguide width. Consider

$$b = X \cdot W_{SIW}, \quad b \approx 2\,\text{mm}. \tag{5}$$

Wide bandwidth can be achieved by using the conventional techniques of adding parasitic patches above the aperture coupled SIW or multilayer designs. However, these techniques increase the conductor losses and surface wave losses due to additional metallic layers involved in the design structures. These losses are even more prominent at 60 GHz. Therefore, in this research work, authors tried as much as possible to avoid the addition of metallic structures over the fundamental SIW design and load the design with DR that consist of only dielectric material. By using the concept of DR, wide bandwidth, high efficiency, and small size antenna/array designs can be achieved. Similarly, the conduction and surface wave losses can be minimized. Wide bandwidth antennas can be designed without compromising antenna efficiency and other good characteristics.

In Figure 4, the DR coupling through aperture is shown. These apertures are the arms of H-shape slot engraved within SIW design. The DR length (L_{DR}), width (W_{DR}), and height (h) are along x-axis, y-axis, and z-axis, respectively. Both of the DR have TE^x_{111} modes of operation [14, 15]. The L_{DR} and W_{DR} are optimized as shown in Figure 5(b). The optimized numerical values are shown in Table 1. At 60 GHz it is recommended that the substrate used in the designs may not have thickness more than quarter-guided wavelength ($\lambda_g/4$). Where λ_g is the guided wavelength in the substrate having permittivity 2.23 and calculated in (6). Consider

$$\lambda_g = \frac{\lambda_0}{\sqrt{\varepsilon_r}} = 3.35\,\text{mm}. \tag{6}$$

The size of the antenna and bandwidths are inversely proportional to the dielectric constant (ϵ_r) of the substrate. To keep the moderate size of the DR so that at 60 GHz it should not be that much minute that it creates problems while fabricating, low permittivity material is chosen. Otherwise, from the literature it is well known that the DR are always used with very high permittivity materials. Furthermore, to achieve wider bandwidth the material is chosen with low permittivity for SIW substrate and DR as well. The material used for DR is RT/duroid 5880 having permittivity $\varepsilon_r = 2.23$ and loss tangent $\tan\delta = 0.003$.

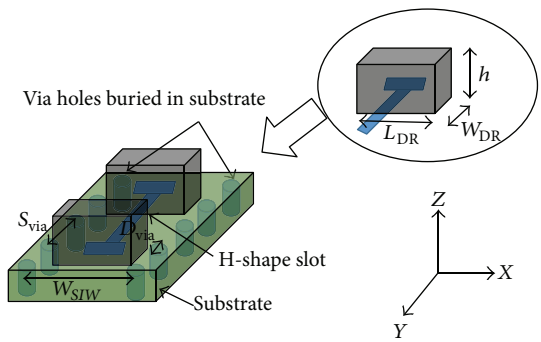


Figure 4: DR coupling through aperture.

Table 1: Antenna design parameters.

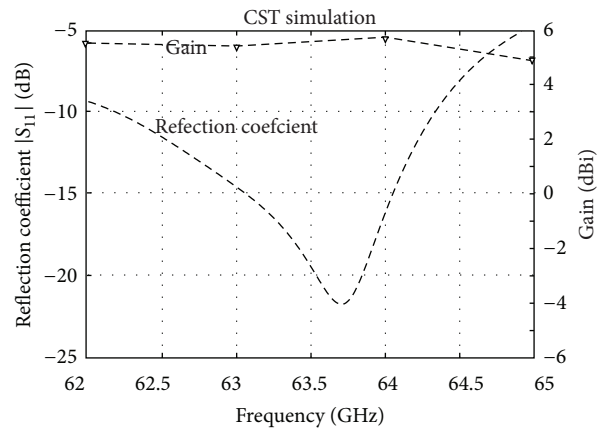
Symbol	Numerical value (mm)
W_{SIW}	2.4
D_{via}	0.50
S_{via}	0.60
W_{trans}	1.9
L_{trans}	2.0
W_S	0.24
L_S	2.6
X_S	0.14
Y_S	3.75
L_{DR}	2
W_{DR}	1.50

As $W_{DR} \gg h$ and $L_{DR} \gg h$, therefore "h" is approximated from (7) [15]. Consider

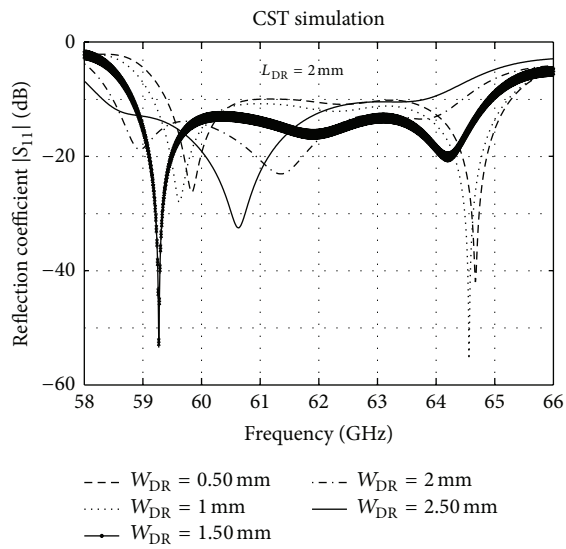
$$h \approx \frac{c}{4 f_0 \sqrt{\varepsilon_r}} = \frac{\lambda_g}{\varepsilon_r} = 0.83\,\text{mm}. \tag{7}$$

The available substrate thickness very close to the approximated value is 0.79 mm. Therefore, it is selected in designs of DR. The optimized numerical values of the design parameters of SIW and DR are given in Table 1.

The reflection coefficient (dB) and the gain (dBi) characteristics using CST Microwave Studio for a SIW single antenna element without DR are shown in Figure 5(a). To achieve wide bandwidth, the fundamental design is loaded with two pieces of DR. Extensive simulation work has been done using CST Microwave Studio software to find the optimum DR position and dimensions along with the slot parameters to combine their resonance frequencies for wide bandwidth operation. The reflection coefficient (S_{11}) optimization results for finding the optimum width with the best value of optimized length of the DR using CST Microwave Studio is shown in Figure 5(b). The optimum results are obtained with DR length (L_{DR}) and width (W_{DR}) of 2 mm and 1.50 mm, respectively. The effect of DR in terms of bandwidth improvement is prominent that can be observed from the results shown in Figure 5(b).



(a)



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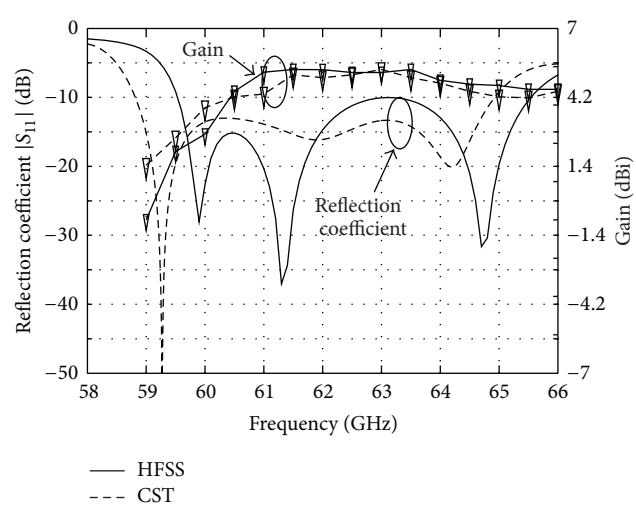

(c)

Figure 5: (a) SIW single antenna element without dielectric resonators (DR), (b) dielectric resonators (DR) parameter optimization, and (c) SIW single antenna element with dielectric resonator (DR).

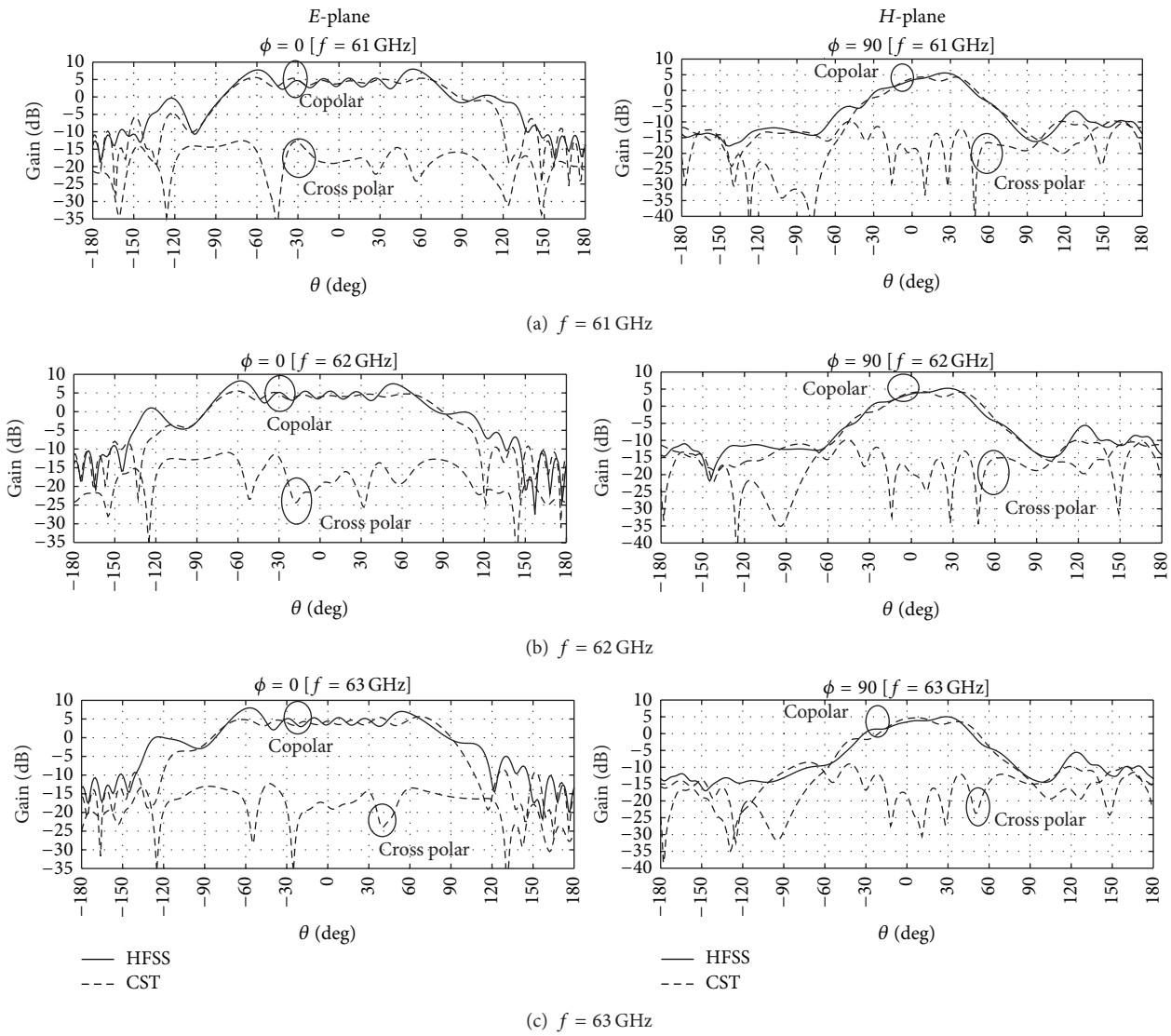

Figure 6: E-plane and H-plane radiation patterns for SIW single antenna element at three frequencies.

In Figure 5(c), the impedance bandwidth is shown for SIW single H-shape slot antenna with optimized DR dimensions. The cumulative bandwidth is achieved by having the resonance from three elements: the long longitudinal section of the slot and the two DR at the top of the small horizontal slot sections. The impedance bandwidth of 10.33% from 58.80 to 65 GHz (6.20 GHz) is achieved by CST Microwave Studio simulation. The gain is found to be flat over the frequency band after 61 GHz with a maximum value of 5.5 dBi at 63 GHz. The estimated efficiency of the antenna is 81%. The results are verified by using HFSS simulation software as shown in the same figure and are found to be in good agreement.

E-plane (horizontal plane, phi = 0) and H-plane (elevation plane, phi = 90) radiation patterns for three frequencies, 61 GHz, 62 GHz, and 63 GHz, are shown in Figure 6. At these frequencies, the 3 dB beam widths for E-plane and H-plane radiation patterns are found to be 155, 156, and 159 degrees and 59, 63, and 62 degrees, respectively. The cross polar ratio is found to be less than −22 dB for all the frequencies in the band for both E-plane and H-plane. The CST and HFSS results are in good agreement with each other.

The wide bandwidth achieved with the SIW single antenna element is sufficient for intended WLAN and WPAN communication applications at 60 GHz. However, at this frequency, the channel losses are very high which can be avoided by deploying high gain antennas. Therefore, the gain of single antenna element is insufficient. To achieve high gain, the design of a linear broadside 1 × 4 array is proposed.

2.2. SIW 1 × 4 Antenna Array. Here the broadside linear 1 × 4 element antenna array is presented. All of the design parameters are same as those of SIW single antenna element explained in Section 2.1. In this case, the antenna array is aligned in horizontal plane (E-plane). The distance between the two consecutive elements of the array is taken as 2.4 mm,

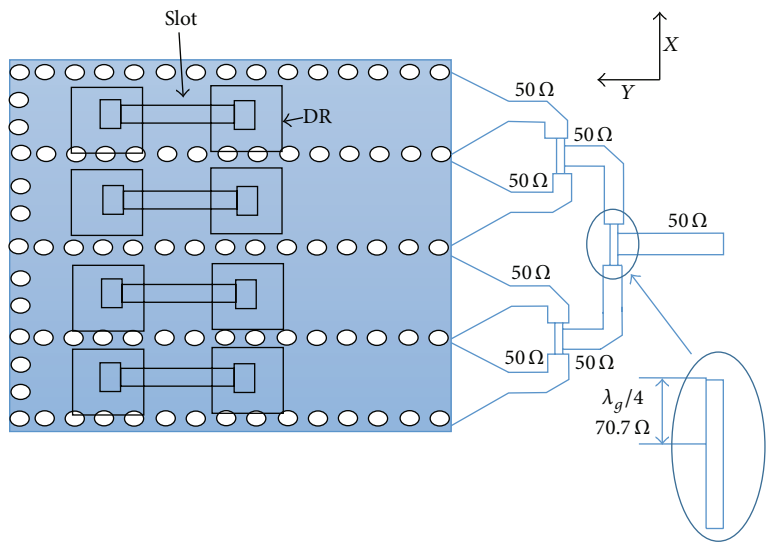

Figure 7: 2-D top view: SIW 1 × 4 antenna array with feeding network.

that is, $0.48\lambda_0$ to keep the metalized via hole walls common between the adjacent elements. The linear array is uniformly excited through a feeding network to achieve high gain. The feeding network consists of three identical 3-dB power splitters. Each power splitter consists of a T-junction in which a 50 Ω microstrip line is connected to two identical branch lines of quarter-wave ($\lambda_g/4$) transformer [16]. The physical length and width of 70.7 Ω quarter-wave microstrip line is 0.93 mm and 0.206 mm, respectively. The antenna array along with feeding network is shown in Figure 7. The total size of the antenna array is taken for the simulations as $10 \times 20\,\text{mm}^2$.

The impedance bandwidth is found to be 10.70% from 59.50 to 65.90 GHz (6.40 GHz) using CST Microwave Studio. The gain is found to be flat after 61 GHz over the frequency band with a maximum value of 11.20 dBi at 65 GHz. The estimated antenna efficiency is 78%. The results are shown in Figure 8. These results are verified using HFSS and are found to be consistent, as shown in the figure.

The E-plane and H-plane radiation patterns are shown in Figure 9. For three frequencies, 61 GHz, 62 GHz, and 63 GHz, the E-plane side lobe levels are −11 dB, −11.50 dB, and −11.15 dB, and 3-dB beam widths are 26 degree, 25 degree, and 25 degree, respectively. The H-plane side lobe levels are −24 dB, −22 dB, and −22 dB, and 3-dB beam widths are 64 degree, 61 degree, and 62 degrees, respectively. The E-plane and H-plane cross polar ratio is less than −25 dB for all the frequencies in the band.

In Table 2, a comparison is performed between the research work presented in this paper and the recent literature produced for antenna design at 60 GHz using SIW technology. The comparison is performed for design structure, bandwidth, gain, and dimensions of the antenna/array. The comparison shows that the proposed antenna/array designs have the advantages over the compared one in terms of design structure, dimensions, and the performance as well.

In [9, 17], the multilayer antenna design approach is adopted. It is well known among the research communities that without very sound and state of the art technical facilities and resources, the multilayer millimeter wave designs are not easy to fabricate. Whereas, in [18], a very thick substrate is used as compared to the one that is used in our designs. By using thick substrates, the conduction losses can be avoided; however, dielectric losses come into play and antenna efficiency can be affected due to surface waves. Therefore, here a moderate approach is adopted while selecting the substrate thickness and design technology. Almost comparable results to the one provided in the referred literature are achieved even with a DR loaded single layer design by using a thin substrate of RT/duroid 5880 with thickness of 0.127 mm, whereas, the compared designs are either multilayered or have the substrates with large thickness.

3. Conclusion

SIW based antenna/array system is investigated at 60 GHz frequency band. A single layer of thin substrate is used in all the designs to avoid dielectric losses and multilayer design complexities. It is shown that wider bandwidth can be achieved by using the concept of DR loaded SIW design structure. The results obtained from CST Microwave Studio are verified using HFSS and they are found to be in good agreement which confirms the accuracy of the proposed antenna/array designs. The proposed design structure is easy to integrate as a front-end component in the RF circuits/components. The use of DR is very effective at 60 GHz RF circuit designs to minimize the conduction losses and surface wave losses that appear in multilayer substrate designs due to metallic layers. This antenna/array will find applications in WLAN, WPAN, and WBAN environments for next generation broadband wireless communication systems.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

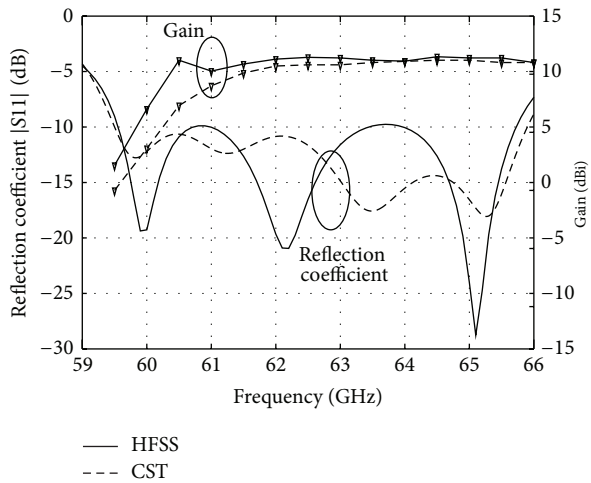

Figure 8: SIW 1 × 4 antenna array reflection coefficient and gain.

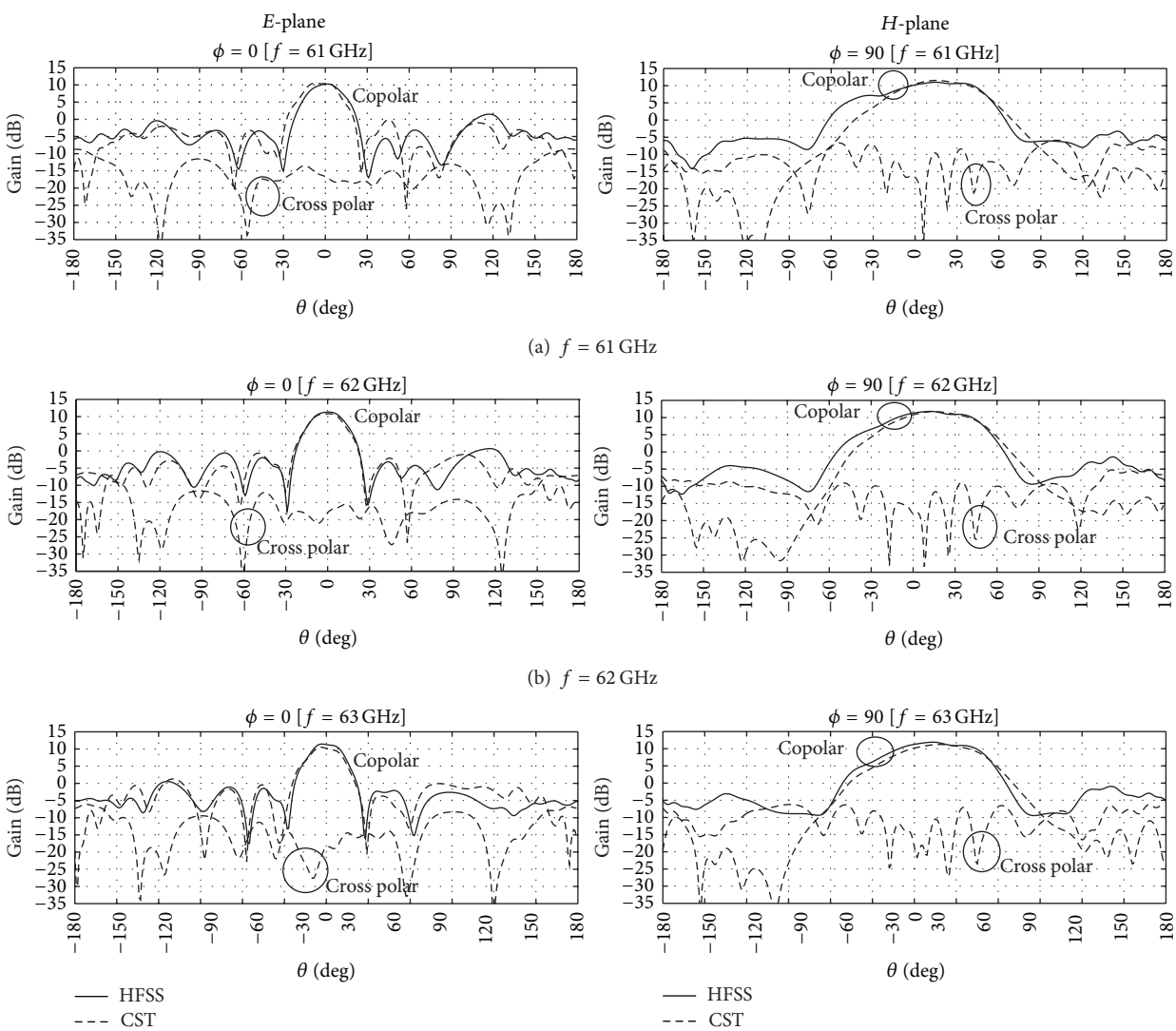

Figure 9: E-plane and H-plane radiation patterns for SIW 1 × 4 antenna array.

Table 2: 60 GHz antenna/array designs and performance comparisons from literature.

Antennas for 60 GHz	Design description		Bandwidth (GHz)	Gain (dBi)	Dimension ($l \times w \times h$ mm^3)
Our work	Single layer design with thin substrate of RT/duroid 5880 having permittivity $\epsilon_r = 2.23$, loss tangent tan $\delta = 0.003$ with thickness 0.127 mm. The DR thickness is 0.79 mm.	Single antenna element	6.20 (58.80–65)	6.6	$10 \times 3 \times 0.952$ (with DR)
			2.70 (58.40–61.10)	6	$10 \times 3 \times 0.162$ (without DR)
		1×4 antenna array	6.40 (59.5–65.90)	11.2	$20 \times 10 \times 0.952$ (with DR)
			2.70 (58.70–61.40)	11.2	$20 \times 10 \times 0.162$ (without DR)
[17]	Multilayer SIW based slot couple patch antenna design that consists of two layers of substrate of RT/duroid 5870 having permittivity $\epsilon_r = 2.33$, loss tangent tan $\delta = 0.002$, each substrate with thickness 0.79 mm	Single antenna element	14 (56.30–70.30)	5	$>15 \times 4.8 \times 1.63$
[9]	Multilayer layer design that consists of two layers of pyralux substrate, each having thickness 0.75 μm with permittivity $\epsilon_r = 2.4$, loss tangent tan $\delta = 0.002$ and one layer of FR4 having substrate thickness of 200 μm.	Single antenna element	5.8 (58.7–64.5)	7.6	$30 \times 30 \times 0.484$
		1×4 antenna array	6.3 (58.7–65)	12.4	$30 \times 30 \times 0.484$
[18]	Single layer design with thick substrate of RO3006 having permittivity $\epsilon_r = 6.15$, loss tangent tan $\delta = 0.003$ with thickness 0.635 mm	Single antenna element	7 (57–64)	7.4	$10 \times 6 \times 0.67$
		2×4 antenna array	7 (57–64)	12	Not given

Acknowledgment

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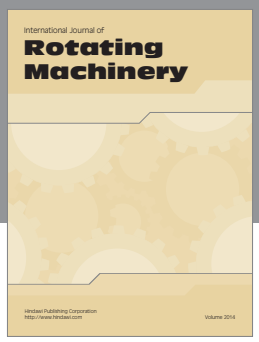

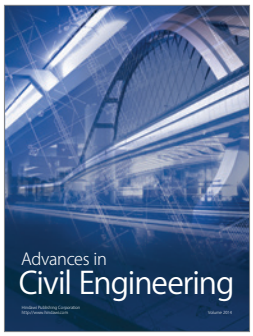

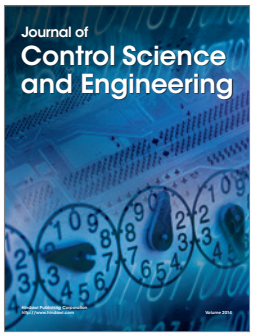

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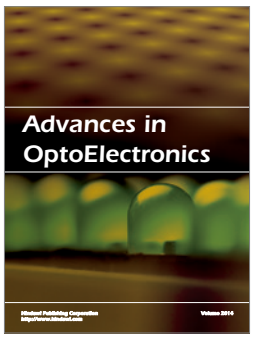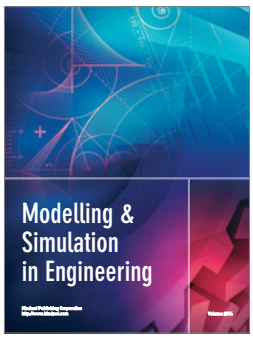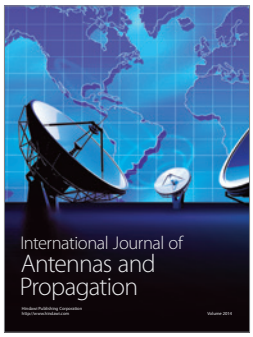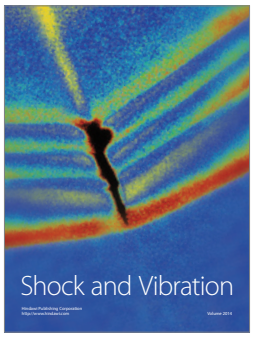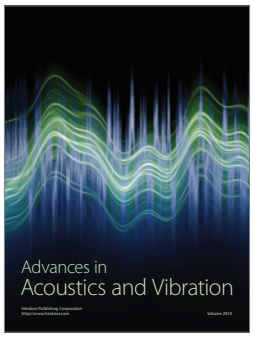
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