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Frequency Transformation to Design Single Band Circular Patch MMW Antennas

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Abstract: This paper introduces novel derived transformation equations to design single band circular antennas for Millimeter Wave (MMW) applications. The design utilizes the approach adopted for MMW antenna design based on an integrated Dielectric Resonator Antenna (DRA) in a Si-based technology platform for 77 GHz MMW applications. The obtained optimized antenna by DRA is used as a reference and the proposed transformation is applied to calculate the new antenna design parameters that satisfy its given specifications without changing the geometry. Four Antennas are demonstrated by using this transformation. The desired frequencies are: 35, 60, 94 and 120 GHz; all lie in the MMW band to be utilized in several applications.

Keywords: Millimeter Wave Antenna or Frequency Transformation.

1. Introduction

EHF or Extremely High Frequency [1] and [2] is a band of radio frequencies in the electromagnetic spectrum designated by the International Telecommunications Union (ITU) range from 30 to 300 GHz; also known as Millimeter Wave (MMW) or band due to the range of wavelengths from 10 down to 1 millimeter.

The most utilized frequencies in the MMW are: 35, 60, 77, 94 and 120 GHz. The radiating frequency 35 GHz [3] lies in the Ka band which is a band of frequencies ranges from 26.5 to 40 GHz can be utilized in many applications; for example, we can use this frequency band in targeting radars on military aircraft with high resolution and close range and satellite communications.

The frequency that radiates at 60 GHz is a part of an unlicensed frequency band that is commonly used for remote sensing applications and astronomy [3], satellites close to 60 GHz utilizes remote sensors to determine the temperature in the upper atmosphere; this process is accomplished by measuring radiations emitted from the molecules of the oxygen that is a function of temperature and pressure. In addition to the previous applications, the 60 GHz can be used to observe the atmosphere in case of climate and meteorological sensing applications. In the meanwhile, the U.S satellite sensors; for example, the Advanced Microwave Sounding Unit (AMSU) on NASA satellite and department of defense satellite in F-16 uses the 60 GHz frequency as the operating frequency. Recently, the new technology approach targets the operating frequency to be near 60 GHz in order to provide high signal directivity (pencil-beam like) that allows distinct systems to operate close to each other without subjecting to

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interference; one of the applications that will embrace this technology is the radar system with high resolution [4]. The upcoming WiFi standard, known as IEEE 802.11ad will operate at the 60 GHz frequency with high data transfer up to 7 Gbps.

The most commonly used frequency band in the industrial bands for many applications is the 77 GHz frequency which is part of the W band that ranges from 75 to 110 GHz. For radar sensors applications [5] and [6], the 77 GHz frequency can be utilized; for example, the FMCW Radar Sensor that is designed by SIVERS IMA [4]. This sensor is used for speed measuring, position and distances for both security and surveillance purposes. In addition to all the previously mentioned applications, it can be used in the design of a radar system to direct an automotive cruise [7]. Automotive 77 GHz radar systems have a very promising future; it permits high accuracy, precision and great scalability from short to long range; this new feature enables the future functions for helping the driver of the car and securing issues in the New Car Assessment Programs (NCAP) [8].

Another very commonly used frequency in the W band that is widely used in many applications is the 94 GHz frequency [9]. A millimeter wave camera for detection of hidden weapons functions at 94 GHz. Also in astronomy applications, the use of 94 GHz frequency in millimeter wave radar imaging applications with security and defense applications. In military applications, there is a less-than-lethal weaponry technology that uses the millimeter waves to make the temperature of a thin layer of the human skin high up to 54^{o}C at a depth of 0.4 nm to pressurize the targeted person to move away; this is done by ejecting bursts last for two second of the 94 GHz focused beam.

As for the 120 GHz frequency; developing in optical communication technology has been taken into consideration for many years [10], the main idea is the conversion of the optical sub carrier signals along with data generated by photonic technology to electrical signals and radio waves by using Uni-Travelling Carrier Photo Diode (UTC-PD).

This paper is organized as follows: Design of high gain, high efficiency circular DRA patch antenna using Si-based technology platform where all components are fabricated using microfabrication technique at the same time is illustrated in Section 2. Equations of the novel transformation technique are introduced in Section 3. The proposed systematic circular antenna design procedure is applied to implement four antennas whose desired specifications and the obtained results are analyzed in Section 4. The conclusions and comparison with others methods are given in Section 5.

2. Design of a Circular Patch Reference Antenna

2.1. Antenna Geometry and Design

A reference antenna will be designed according to the design rules to radiate at a certain desired frequency in the MMW range. One of the designs [11] already implemented is an integrated Dielectric Resonator Antenna (DRA) on a Si-based technology platform is designed to operate at 77 GHz millimeter wave applications. The DRA is excited using coplanar waveguide feed (CPW). This design declaims the performance of high gain on-chip DRA on low conductive silicon (conductivity 0.01S/m). The proposed DRA antenna element has a 2 GHz bandwidth and a 4.78 dB gain with 98% radiation efficiency. This antenna witnesses a great enhancement in performance by comparing it with previously reported antennas [12], [13], [14], [15] and [16].

The designed circular antenna is shown in Figure 1. A co-planar strip line of signal width, S = 0.2 mm, length, S_1 = 1 mm, g_1= 0.7 mm and gap width g = 0.1206 mm, is etched on the gold coated ground plane of length x width, L x W = 1.5 x 1.5 mm, and thickness t_g = 0.002 mm, is shown in Figure 1(a) and (b). A low conductive silicon (conductivity = 0.01 s/m) DR material was used as the radiating element. The dimensions of the Circular DRA: d_1= 0.4 mm and d_{DRA}=1.2mm; is as shown in Figure 1 and summarized in Table 1.

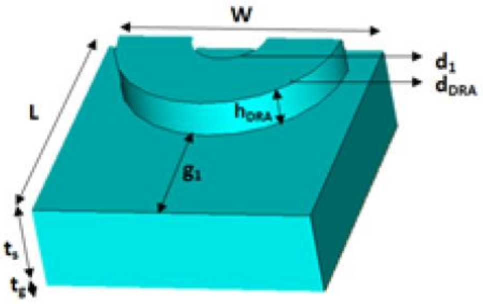

Fig. 1. (a) Circular geometry of the designed DRA; (b) CPW feed of the designed DRA.

Table 1. Dimensions of the designed circular antenna

Dimension	L	W	t_s	t_g	g_1	g	S	S_1	d_1	d_{DRA}	H_{DRA}
Value (mm)	1.5	1.5	0.475	0.002	0.7	0.1206	0.2	1	0.4	1.2	0.2

2.2. Circular Antenna Simulation

Using a simulation tool, in this case IE3D, it is shown from Figure 2 that the simulated return loss, S_{11} indicates that this antenna radiates at a frequency of 76.998 GHz and S_{11} of -21.7227 dB. So, no need for optimization. Using IE3D simulation tool, Figure 2 shows the resulting S_{11}. The antenna now radiates at 76.998 with -21.7227dB and a band width of 15.7992 GHz and antenna efficiency of 98.539%. The other designed antenna parameters such as: Band Width, BW, efficiency, e_o is shown in Figure 3 and gain, G is shown in Figure 4.

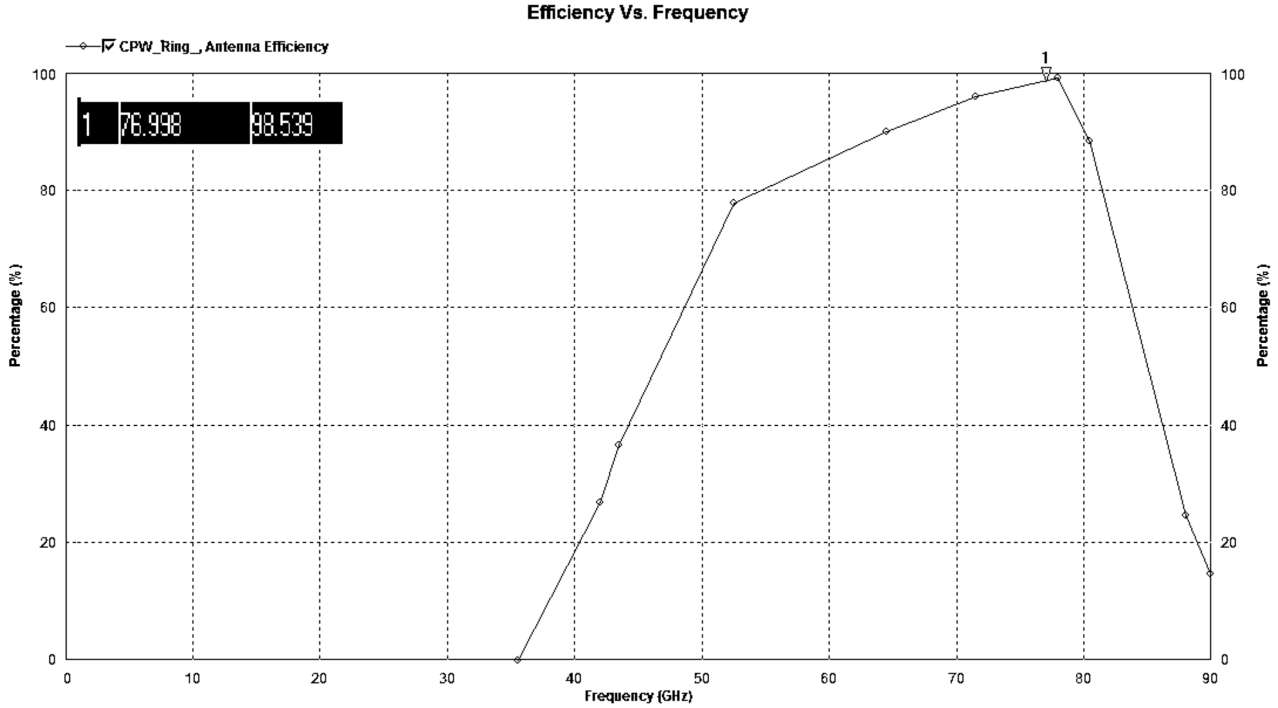

Fig. 2. Circular CPW Feeding Simulated Antenna Efficiency of the Optimized Antenna

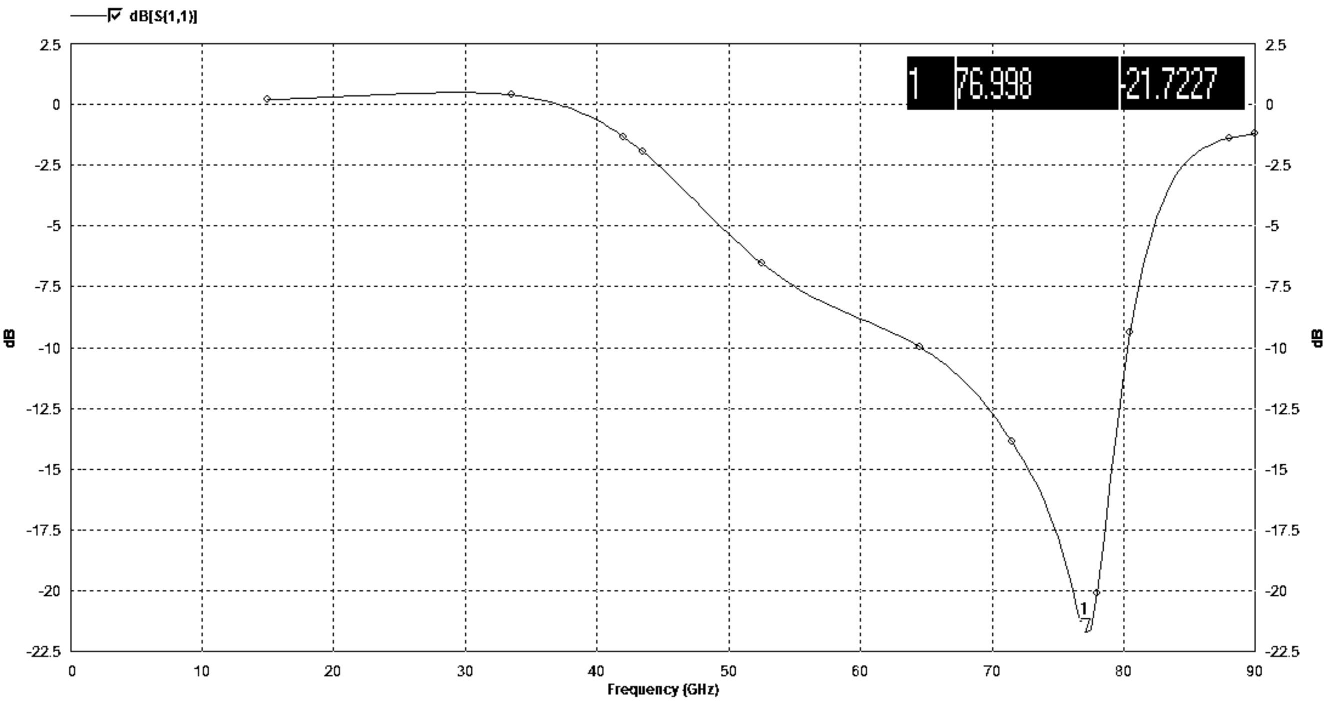

Fig. 3. Circular CPW Feeding Simulated Return Losses (S_{11}) of the Designed Antenna.

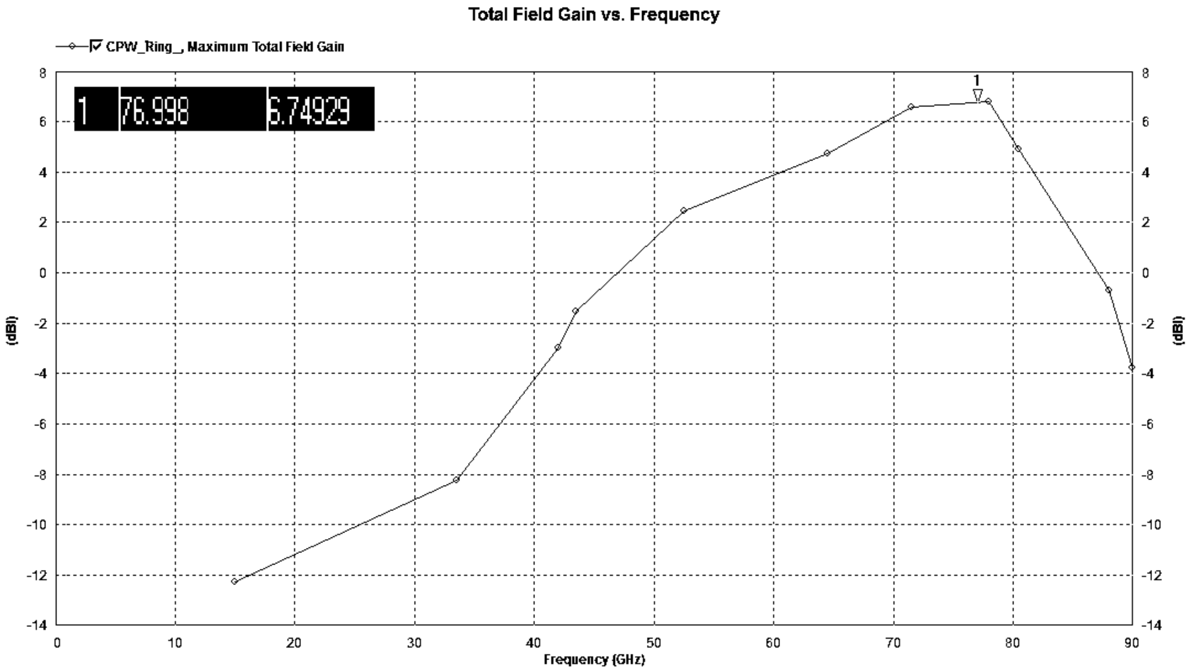

Fig. 4. Circular CPW feeding simulated gain, G of the optimized antenna

3. Generic Transformation for Single Band Antenna

Section 2 illustrates an optimized MMW single band antenna designed based on Dielectric Resonator Antenna (DRA) in a Si-based technology platform for 77 GHz MMW applications. The obtained results shown in Figure 3 to Figure 5 and Table 2 to Table 3 satisfy the desired antenna design specification. Therefore, we will take this design as reference and then derive generic transformation equations to be utilized to design any single band antenna with arbitrary specifications.

To design an antenna working on a certain frequency (single band), we first need to make some analytical calculations, use a simulation tool to get results then make several optimizations processes for more accurate results which in most of the cases it is considered to be a very exhausting process with no confirmation of reaching an excellent design.

However, there must be easier steps to design an antenna, going through all the designing steps will be time consuming, unless there is a method to get the new design based on a previously designed one, without the need for complex calculations and without the need for analytical analysis and initial design steps.

It is well known that the frequency is inversely proportional to the length; means to increase frequency, the lengths of the parameters must be decreased and vice versa; this information will be considered in designing new antennas based on a reference one.

Define a ratio; R_{ref} represents the ratio between resonance frequencies: designed frequency, $f_{designed}$ and desired frequency, $f_{desired}$ as:

$$R_{ref} = \frac{f_{designed}}{f_{desired}} \tag{1}$$

Equation (1) represents the frequency transformation. This ratio will be considered as a reference to normalize the corresponding ratios when designing any other desired antenna as will be illustrated in the following section.

The idea is to get a previously designed antenna, optimize it as much as possible to use it as a reference antenna then using it to build a new design by multiplying the old dimension lengths with this ratio, R_{ref}. The resulting dimensions will lead to the new antenna design.

$$L_{desired} = L_{designed} x R_{ref} \tag{2}$$

Equation (2) represents the Frequency Transformation Equation.

Finally, do only one optimization step by using the same ratio but with the obtained dimension, and then new antenna for the desired operating frequency is obtained without wasting time in designing it from scratch.

$$L_{optimized} = L_{designed} x R_{ref} \tag{3}$$

Equation (3) represents the Optimization Equation.

The following section illustrates the utilization of the frequency transformation and optimization equations: (1), (2) and (3) of the reference antenna that radiates at 77 GHz to 35, 60, 94 and 120 GHz antennas.

4. Applications

4.1. Design of a Circular MMW Antenna with Operating Frequency 35 GHz

To design the antenna geometry to have radiating frequency of 35 GHz, first apply Equation (2) to obtain the values of the dimensions of the desired design as follows.

$$L_{35} = L_{76.998}\, x\, \frac{76.998}{35}$$

As a result, the dimensions of the desired antenna are listed in Table 2.

The obtained S_{11} curve after simulation is shown in Figure 5. The antenna radiates at 35.502 GHz with -16.8013 dB, bandwidth of 3.22746 GHz; these results need optimization.

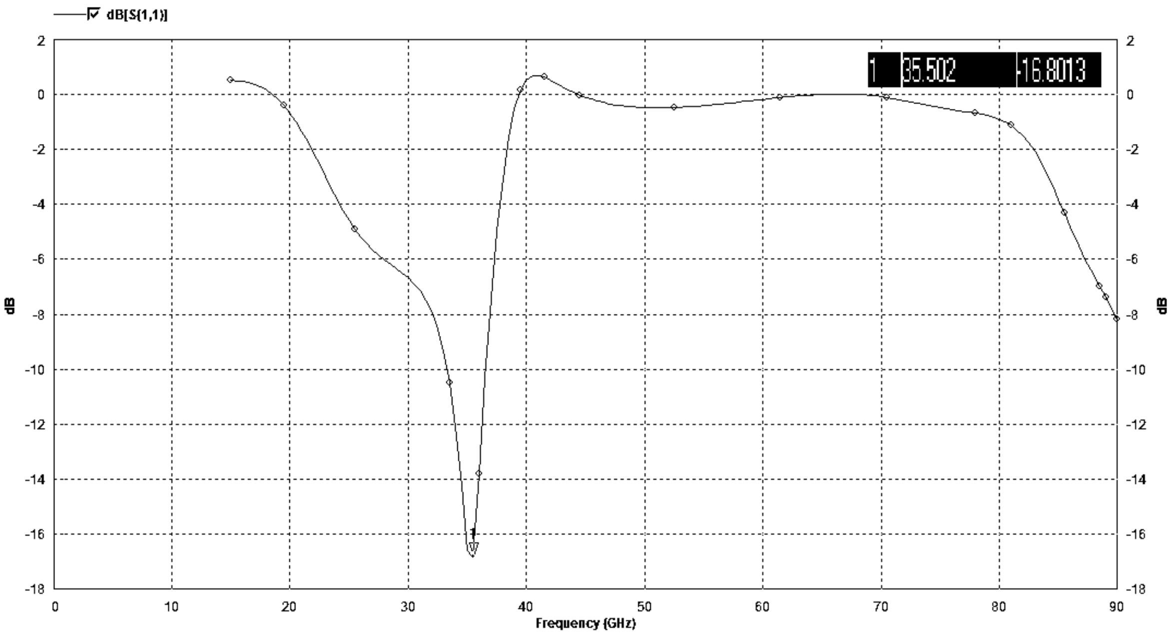

Fig. 5. S_{11} Curve for the designed circular antenna at operating frequency 35 GHz

Table 2. Dimensions of the desired circular antenna working at 35 GHz

Dimension	L	W	t_s	t_g	g_1	g	S	S_1	d_1	d_{DRA}	H_{DRA}
Value (mm)	3.3	3.3	1.045	0.0044	1.54	0.2653	2.2	0.44	0.0.88	2.6399	0.44

For optimization, Equation (3) is used and the result is shown in Table 3.

$$L_{35} = L_{35.502}\, x\, \frac{35.502}{35}$$

Table 3. Dimensions of the optimized circular antenna working at 35 GHz

Dimension	L	W	t_s	t_g	g_1	g	S	S_1	d_1	d_{DRA}	H_{DRA}
Value (mm)	3.3474	3.3474	1.06004	0.00446	1.562	0.2691	0.4464	2.2316	0.8926	2.6778	0.4463

Summary of the antenna parameters are listed in Table 4 and the performance parameters are shown in Figure 6.

Table 4. Parameters of the optimized circular antenna working at 35GHz.

Parameter	Operating Frequency, f	Band Width, BW	Gain, G	Efficiency, e_o
Value	35 GHz	3.22746 GHz	6.88587 dBi	97.8769 %

To reach a result near this with the conventional design rules, many steps will be considered in designing then more steps will be considered in optimizing the result to reach the desired radiating frequency.

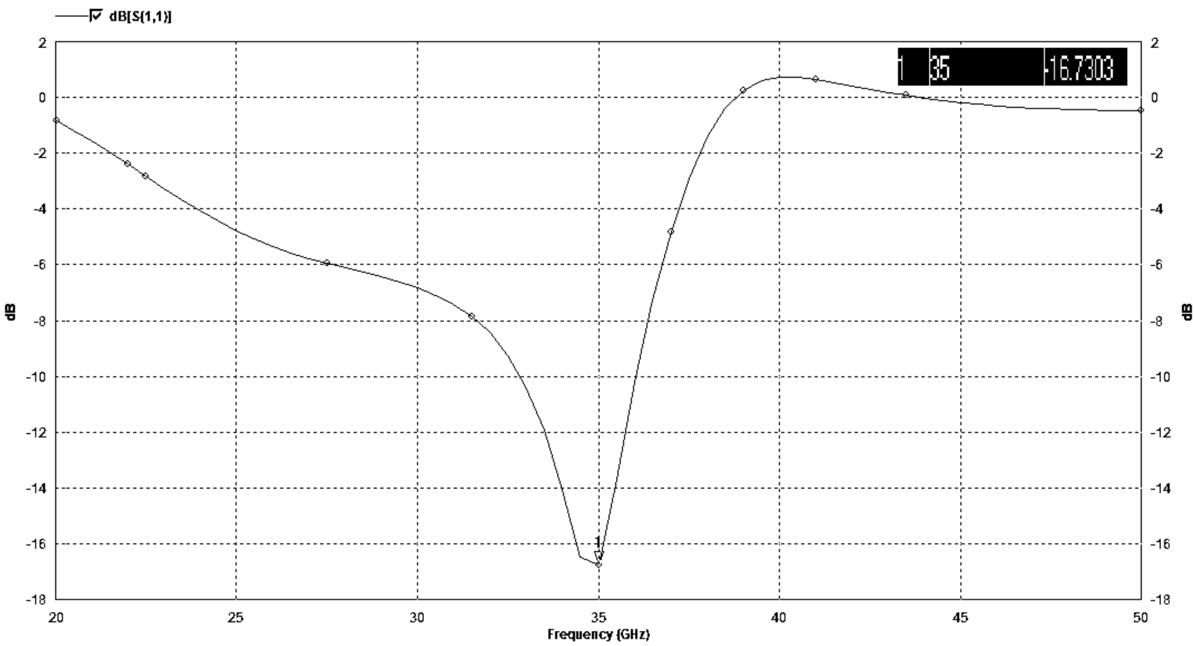

Fig. 6. S_{11} Curve for the optimized circular antenna at operating frequency 35 GHz

4.2. Design of a Circular MMW Antenna with Operating Frequency 60 GHz

Now, we would like to transfer the radiating frequency from 77 to 60 GHz. Instead of going through all the design methods; analytical design, initial design using simulation tool and finally, performing several optimization steps to obtain the desired radiating frequency, we can simply use a very simple ratio based on the results obtained from the reference antenna to reach the desired frequency.

The idea is simple. Since we simulated the reference antenna to find the exact radiating frequency, which is 77.0041 GHz (not 77 GHz, precision is very important to obtain good results without wasting time in optimization steps) and the desired new frequency is 60 GHz, doing the calculations in Equation (2) to reach the new design with the required frequency.

$$L_{60} = \frac{76.998}{60}\ x\ L_{76.998}$$

The geometry is the same as the reference antenna except for the scale; the dimensions of the new antenna are listed in Table 5

Table 5. Dimensions of the desired circular antenna working at 60 GHz

Dimension	L	W	t_s	t_g	g_1	g	S	S_1	d_1	d_{DRA}	H_{DRA}
Value (mm)	1.925	1.925	0.6095	0.00257	0.8983	0.1548	0.2566	1.2833	0.5134	1.54	0.2567

The S_{11} curve is shown in Figure 7 using IE3D simulation tool, it is very important to increase the lengths with the same ratio and to maintain the shape of the antenna.

As the lengths increase, the radiating frequency will decrease; we consider radiation of a certain frequency if the S_{11} value is -10 dB or less.

The radiating frequency for Figure 7 is at 60 GHz and a bandwidth of 6.19598 GHz. So, this result was very satisfying and now we have an antenna designed at 60 GHz with minimum effort and time consumption which is ready to be used in many applications as described before. Summary of the parameters are listed in Table 6.

Table 6. Parameters of the optimized circular antenna working at 60GHz

Parameter	Operating Frequency, f	Band Width, BW	Gain, G	Efficiency, e_o
Value	60 GHz	6.19598 GHz	7.10103dBi	98.4166%

4.3. Design of a Circular MMW Antenna with Operating Frequency 94 GHz

To transfer the radiating frequency of the antenna to 94 GHz, a similar approach of that of 35 and 60 GHz will be considered, using Equation (2) to transfer the frequency.

$$L_{94} = \frac{76.998}{94} \, x \, L_{76.998}$$

As a result, all the lengths of the derived antenna will be smaller than that of the reference one; this is because the frequency is inversely proportional to the length. After calculation, the dimensions of the new antenna are listed in Table 7.

Table 7. Dimensions of the Desired Circular Antenna Working at 94 GHz

Dimension	L	W	t_s	t_g	g_1	g	S	S_1	d_1	d_{DRA}	H_{DRA}
Value (mm)	1.2286	1.2286	0.38906	0.00164	0.5734	0.0988	0.1638	0.8191	0.3276	0.983	0.1638

Using IE3D tool to obtain the result of S_{11} shown in Figure 8, the resulted radiating frequency is at 93.5656 GHz with bandwidth of 20.3279 GHz, close to 94 GHz, but further optimization (only one step) can be done to reach a more precise value approximately equals to 94 GHz.

To reach a more precise and very close design to 94 GHz, the same idea is used by multiplying the lengths by a factor of Equation (1). From Equation (3) we get:

$$L_{94} = \frac{93.5656}{94} \, x \, L_{93.5656}$$

The new and optimized antenna parameters are calculated and listed in Table 8.

Table 8. Dimensions of the optimized circular antenna working at 94 GHz

Dimension	L	W	t_s	t_g	g_1	G	S	S_1	d_1	d_{DRA}	H_{DRA}
Value	1.223	1.223	0.163	0.00163	0.5709	0.0984	0.163	0.8154	0.326	0.9784	0.123

The S_{11} curve obtained using IE3D simulation tool is as shown in Figure 9, after using only one optimization step, the new antenna design radiates at 94.0164 GHz and 20.3279 GHz bandwidth. Table 9 summarizes the antenna parameters.

Now we have an antenna design that radiates at 94 GHz with negligible error.

Table 9. Parameters of the optimized circular antenna working at 94 GHz

Parameter	Operating Frequency, f	Band Width, BW	Gain, G	Efficiency, e_o
Value	94.0164Hz	20.3279 GHz	6.87148 dBi	98.1149 %

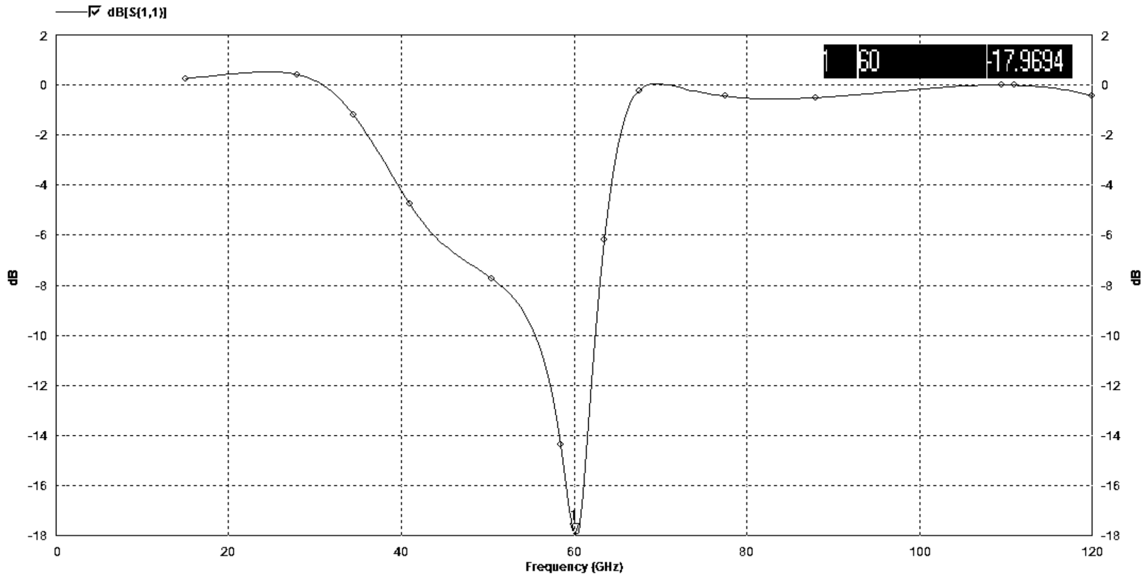

Fig. 7. S_{11} Curve for the designed circular antenna at operating frequency 60 GHz

4.4. Design of a MMW Antenna with Operating Frequency 120 GHz

Now we need to transfer the radiating frequency from 77 GHz to 120 GHz, the use of 120 GHz is very important in several applications mentioned in a previous section.

To transfer frequency, the design Equation (2) is used with the same idea as before.

$$L_{120} = \frac{77.998}{120}\ x\ L_{77.998}$$

With the same geometry except for antenna size, the new dimensions are listed in Table 10.

Table 10. Dimensions of the desired circular antenna working at 120 GHz

Dimension	L	W	t_s	t_g	g_1	g	S	S_1	d_1	d_{DRA}	H_{DRA}
Value (mm)	0.9624	0.9624	0.30482	0.00128	0.4492	0.0773	0.1284	0.6416	0.2566	0.77	0.1283

The S_{11} curve is shown in Figure 10 using IE3D simulation tool, it is very important to decrease the lengths with the same ratio and to maintain the shape of the antenna, as the lengths decreases, the radiating frequency will increase.

The radiating frequency is at 118.525; we can either accept this result as it is near to 120 GHz or we can make optimization once.

We can use the simple ratio in Equation (1) to make optimization, instead of 77.998, we can write 118.525 using Equation (3).

$$L_{120} = \frac{118.525}{120}\ x\ L_{118.525}$$

The dimensions of the optimized antenna are listed in Table 11.

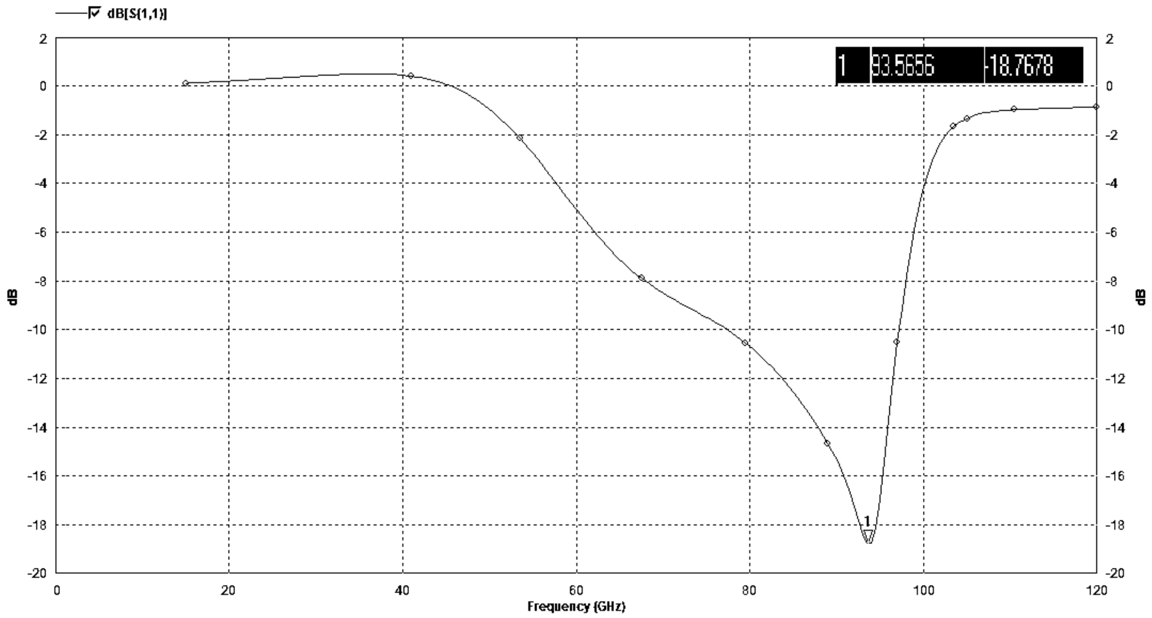

Fig. 8. S_{11} Curve for the designed circular antenna at operating frequency 94 GHz

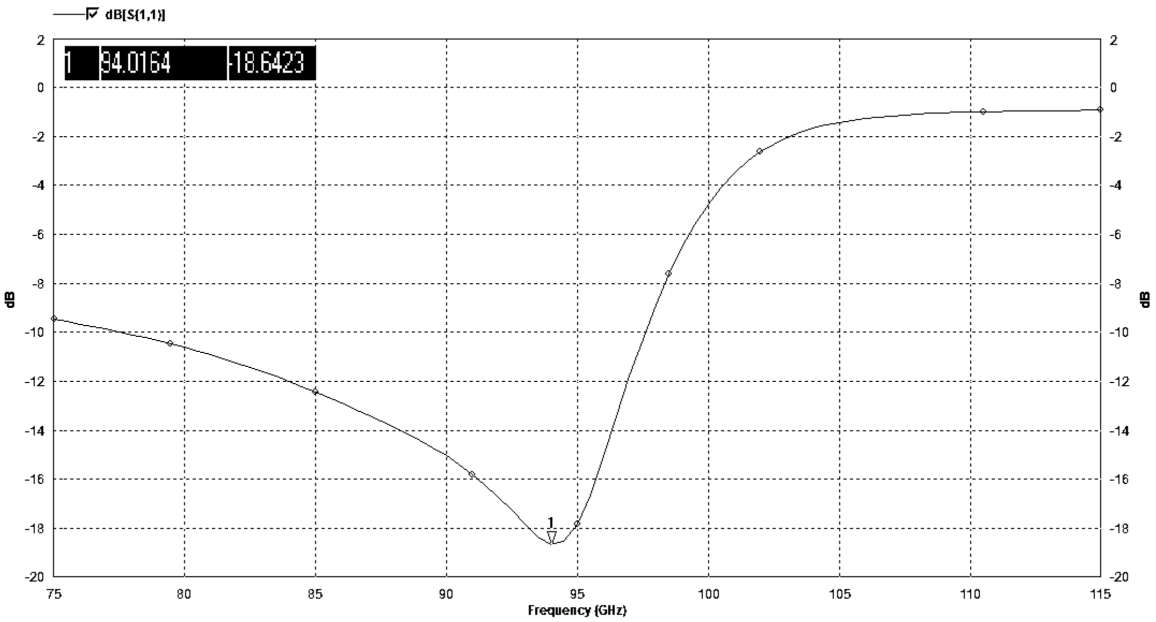

Fig. 9. S_{11} Curve for the optimized circular antenna at operating frequency 94 GHz

Table 11. Dimensions of the optimized circular antenna working at 120 GHz

Dimension	L	W	t_s	t_g	g_1	g	S	S_1	d_1	d_{DRA}	H_{DRA}
Value (mm)	0.9505	0.9506	0.30104	0.00126	0.4437	0.0764	0.1268	0.6337	0.2534	0.7606	0.1268

The lengths of the parameters after optimization were smaller than that before optimization, this means the results were predicted, after optimization the radiating frequency is at 120.015 GHz as shown in Figure 11 with frequency error 0.0125% which is approximately 120 GHz and 29.9795 GHz bandwidth. So, these results were very satisfying. The summary of the parameters is listed in Table 12.

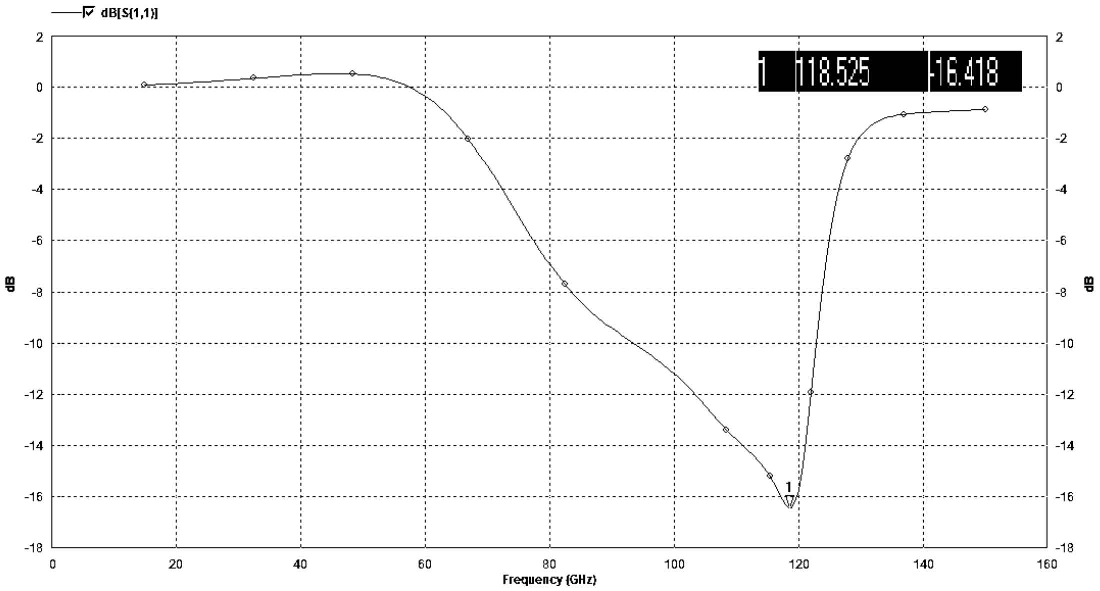

Fig. 10. S_{11} Curve for the designed circular antenna at operating 120 GHz

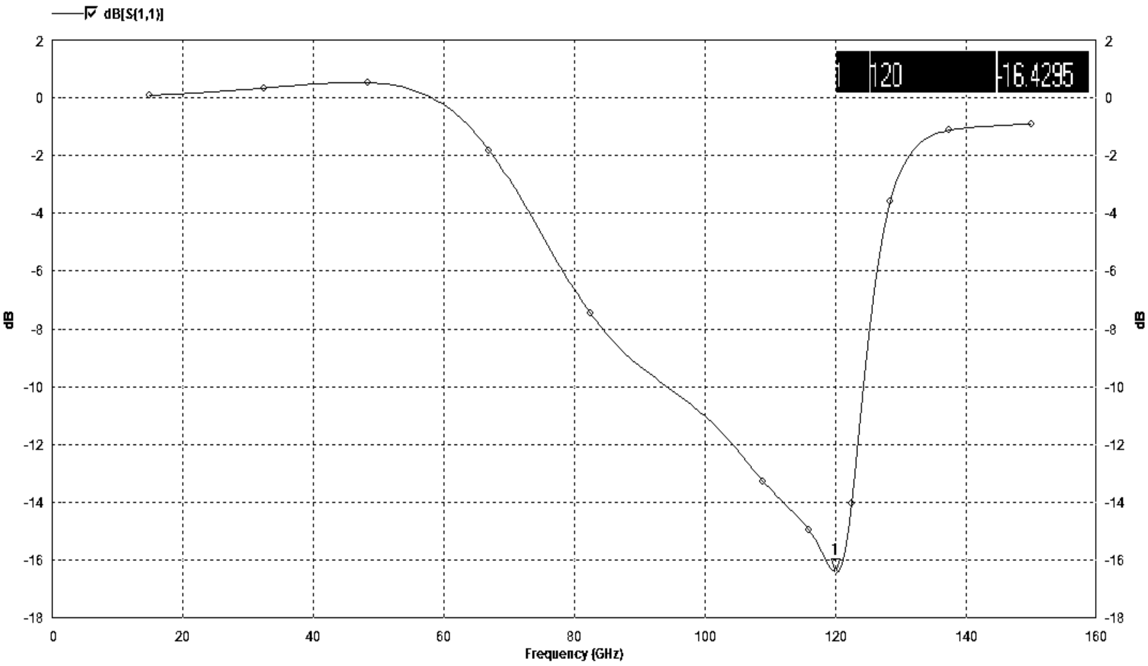

Fig. 11. S_{11} Curve for the optimized circular antenna at frequency 120 GHz

Table 12. Parameters of the optimized circular antenna working at 120 GHz

Parameter	Operating frequency, f	Band width, BW	Gain, G	Efficiency, e_o
Value	120 GHz	29.9795 GHz	6.63667 dBi	96.3396 %

5. Conclusion

In this paper, a novel transformation technique and design equations are derived to design single band circular antennas for Millimeter Wave (MMW) applications. An integrated Dielectric Resonator Antenna (DRA) in a Si-based technology platform is used to design a reference antenna. Then the derived transformation and design equations are applied to transform this reference antenna to other desired MMW antennas with desired specifications different from the reference one. In order to demonstrate the validity of this approach, four typical examples for MMW antennas that are used in different wireless communication are designed and simulated. The obtained results of these designs indicate that this technique is easy, fast, generic and accurate.

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