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Millimeter wave dielectric loaded exponentially tapered slot antenna array using substrate integrated waveguide for gigabit wireless communications

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Abstract: A new and upcoming application is the use of 60 GHz antennas for high date rate point-to-point connections to serve Gigabit (Gi-Fi) wireless communications. The design of Millimeter wave (MmW) antennas has to cope with the unadorned influences of manufacturing tolerances and losses at 60 GHz. In this paper, the concept of Substrate Integrated Waveguide (SIW) and Exponentially Tapered Slot (ETS) antenna were used together to design a high gain, efficient planar dielectric loaded antenna for MmW Gi-Fi wireless communications at 60 GHz. The SIW is used to feed the antenna and a dielectric is utilized in front of the antenna to increase the gain. The dielectric loaded ETS antenna and compact SIW feed were fabricated on a single substrate, resulting in low cost and easy fabrication. The antenna with elliptical shaped dielectric loaded was fabricated using printed circuit board process. The measured gain of the single element antenna is 10.2 dB, while the radiation efficiency of 96.84% is obtained at 60 GHz. The Y- junction SIW power divider is used to form a 1 × 4 array structure. Measured gain of the 1 × 4 array antenna is 13.3 dB, while the measured radiation pattern and gain are almost constant within the wide bandwidth of the antenna.

Key words: millimeter waves, 60 GHz, exponentially tapered slot antenna, dielectric loading, substrate integrated waveguide

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Introduction

The MmW technology system and applications have been one of the newest topical discussions among researchers around the globe in technical sessions, and commercial boardrooms[1-2]. Strong and growing interest in this incredible specific electromagnetic spectrum is being fueled by its capability of bridging the gap between electronics and wireless communications. The 60 GHz technology offers various recompenses over present wireless communication systems. One of the deciding factors that mark 60 GHz technology gaining significant interest recently is due to the huge unrestricted bandwidth, up to 7 GHz [3-4]. This huge bandwidth represents great potentials in terms of capacity and flexibility that makes 60 GHz technology attractive for incredible gigabit wireless applications.

Antennas with excellent design can improve the performance of wireless communications, particularly at millimeter frequencies. Many types of antenna structures are considered not suitable for 60 GHz applications due to the requirements for low cost, small size, and light weight. In addition, 60 GHz antennas also are required to operate with constant gain and high efficiency over the broad frequency range. Recently, the technology of planar integrated antenna[5] has been developed for MmW applications due to the trend of the integration in radio frequency front-end circuits and systems. As the operating frequency of wireless systems moves into MmW range in order to provide gigabits per second service, there is an increasing incredible demand of high gain antennas used for consumer devices. The desired antenna has to be compatible with integrated circuits, and possess high gain and small side lobe. The antenna, when integrated into consumer devices, should also have the benefits of small size and low production cost[6].

The conventional waveguide technology is still the mainstream for designing high performance MmW based wireless systems. However their relatively high cost and difficult integration prevent them from being used in low

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cost, high volume applications. In addition, the traditional waveguide technique cannot be used to reduce the weight and volume[7]. The concept of SIW technology makes it possible to realize the waveguide in a substrate and provides a sophisticated way to integrate the waveguide with MmW planar circuits using the conventional low-cost printed circuit technology. In particular, a number of SIW based slot antennas have been reported in recent years[8-10]. These antennas consist of single layer of dielectric substrate and are fed from one end through a coplanar feed network which significantly increases the size of the antenna. Furthermore, radiation from microstrip feed lines and junctions severely negotiate the low side lobe level of the slot antenna and increases cross polarization.

Therefore, this work addressed challenges in designing dielectric loaded ETS antenna utilizing SIW technology for the realization of Gi-Fi wireless communications, particularly at 60 GHz using 3D electromagnetic software CST Microwave Studio. Comparison with Ansys HFSS validated the design procedure.

1 Antenna Design

The ETS antenna is also known as flared notch antenna, one of the most promising antenna satisfying all requirements[11]. It is basically a planar traveling wave antenna with end fire radiation. This antenna is the preferred candidate for MmW applications due to its wide bandwidth, low cross polarization and highly directive patterns. A major advantage of this antenna type is that the wide bandwidth and maximum gain can be achieved using exponentially tapered profiles with dielectric loading[12]. The proposed dielectric scheme provides an interesting alternative. This antenna is integrated using a single substrate. It is easy to fabricate and the structure is compact[13]. To eliminate the higher order modes in the waveguide, the thickness of the substrate is restricted. The loaded dielectric slab in front of the antenna can be considered as a dielectric guiding structure excited by the exponential flare resulting in a wider beamwidth and maximum gain. The compact MmW antenna with dielectric loading can achieve a broadband performance and offer several advantages over other counterparts such as relatively low insertion loss, better VSWR, good design tolerance and circuit size compactness[14-15].

A. *Replacing waveguides with equivalent SIW*

At MmW frequencies waveguide devices are preferred; though, their manufacturing process is challenging. Hence, the SIW technology makes it possible to realize the waveguide in a substrate and provides a sophisticated way to integrate the waveguide with MmW planar circuits [16-19]. Here, the dielectric filled waveguide is transformed to SIW by the support of vias for the side walls of the waveguide. In the SIW design the following condition are required,

The metalized via hole diameter is

$$d < \lambda_g/2 \quad . \qquad (1)$$

The spacing between the via holes is

$$P < 2d \quad . \qquad (2)$$

The physical width of SIW is

$$a = a_d + (d^2/(0.95p)) \quad . \qquad (3)$$

The calculated values of the physical width of SIW is 2.0 mm, metalized via hole's diameter is 0.30 mm, and space between the via holes is 1.0 mm.

B. *Microstrip to SIW transition*

The microstrip line is used to transfer the power to antenna. This transmission line is connected to the feed waveguide in the bottom layer. The transition between microstrip line and SIW is critical for achieving good impedance matching and small return loss. A tapered transition was suggested which is useful in most applications[20]. In our transition, the width of 50 Ω microstrip line is like to the width of SIW physical width to achieve impedance matching with low insertion loss and nullify the higher order modes. The width of the 50 Ω microstrip line is 2 mm.

C. *Design of the antenna*

The ETS antenna radiating tapered profile is described by an exponential function. The antenna is excited via the microstrip line to SIW transition. The transition construction exploits wideband features of a microstrip radial stub used as a virtual wideband short. The microstrip is virtually shunted to the second half of the strip line metallization while the first half serves as a ground metallization for the microstrip line. It is necessary to transform the impedance of the input feeding microstrip line to the input impedance of the transition. Therefore, the linear microstrip taper is used as the input impedance transformer[21]. Instead of using the wideband balun, a SIW has been employed to feed the antenna.

To comply with the antenna board dimensions and slot line parameters, the following exponential taper curve definition equation is used[22-23],

$$y = C_1 e^{ax} + C_2 \quad , \qquad (4)$$

where 'a' is the rate of opening the exponential taper, and C1 and C2 can be calculated by the starting and ending points of the taper $P_1(x_1, y_1)$ and $P_2(x_2, y_2)$,

$$C_1 = (y_2 - y_2)/(e^{ax_2} - e^{ax_1}) \quad , \qquad (5)$$

$$C_2 = (y_1 e^{ax_2} - y_2 e^{ax_1})/(e^{ax_2} - e^{ax_1}) \quad . \qquad (6)$$

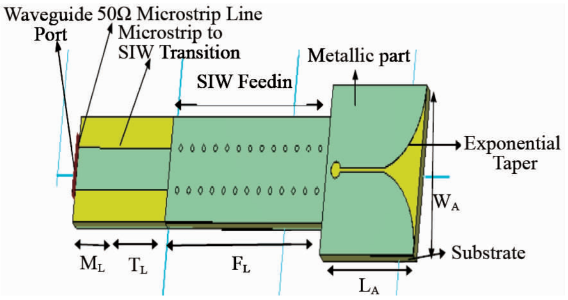

Fig. 1 ETS antenna without dielectric loading

Figures 1-3 illustrate layout of a modeled SIW based ETS antenna without, rectangular, and elliptical dielectric loading, respectively.

Table 1 shows the parameters of the antenna obtained using above equations. The shape of the curvature influences the traveling wave in two main areas. The first is the beginning of the taper and the second is the wide end of the taper. On both places, a reflection of the traveling wave is likely to occur . Therefore , smoother taper

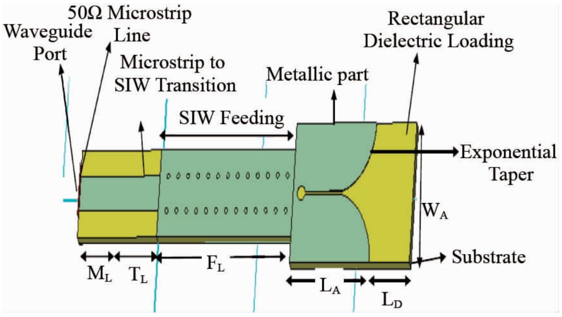

Fig. 2 ETS antenna with rectangular dielectric loading

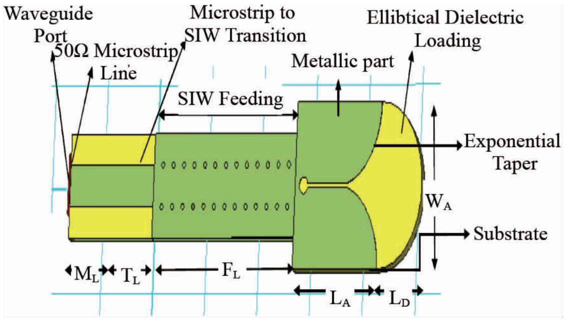

Fig. 3 ETS antenna with elliptical dielectric loading

Table 1 Dimensions of the antenna

Symbol	Value (mm)
L_A	8
W_A	8
L_D	4
F_L	13.5
T_L	5
M_L	3

in the neck minimizes the reflection there[24-25]. This can be achieved with higher value of ‘a’. The beamwidth in the H plane can be controlled through the flare in the H plane. The beamwidth in the E plane is determined by the flare in the E plane that is limited. In some applications, a wider beamwidth in the E plane is also desired. For this purpose, a dielectric slab is placed in front of the antenna. This slab serves as the dielectric guiding structure in the E-plane. In the H-plane, for an antenna with maximum gain, the flare phase distribution along the H plane is nearly uniform without the dielectric loading.

D. *Optimization of ETS Antenna*

The SIW based ETS antenna with elliptical dielectric loading was modeled utilizing CST Microwave Studio. Once the model has been formulated, an optimization algorithm can be used to find its best solution. The newly implemented trust region framework algorithm can work out the sensitivity information to cut down optimization time vividly. The yield analysis for complex three dimensional models is now available at virtually no additional computational rate. According to the target of this antenna at 60 GHz, the radius of vias was modified to provide a better return loss. The parameter ‘d’ was swept from 0.135 to 0.165 mm using trust region framework algorithm to find the best performance of the antenna. A new trust region framework algorithm is very efficient for a direct 3D EM optimization especially in conjunction with the sensitivity analysis[26].

E. *Simulation and measurement*

The antenna structure is simulated without dielectric loading using 3D electromagnetic software CST Microwave Studio as shown in Fig. 1, the gain is 7.2 dB, main lobe direction is 81°, return loss is-12.07 dB, VSWR is 1.66 and side lobe level is-4.0 dB. A rectangle and elliptical dielectric loading is placed in front of the antenna flare to increase the gain, reduce the side lobe level of the antenna and respective structures are shown in Fig. 2 and Fig. 3.

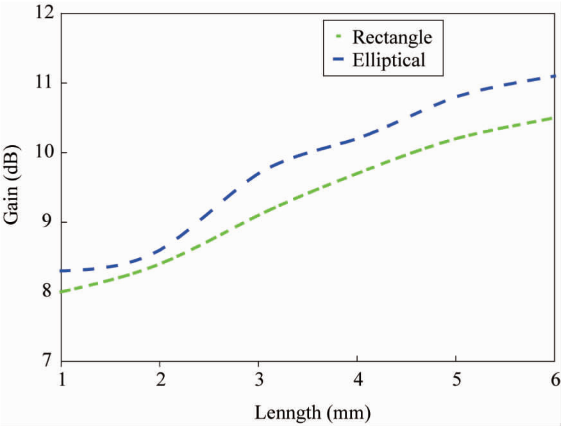

Fig. 4 Gain versus length of the dielectric loading

Figure 4 shows that the elliptical dielectric loading gives higher gain compared with the rectangle dielectric loading with the same length. When the length of dielectric loading is 4 mm, the gains of rectangle and elliptical are 8.3 dB and 10.2 dB, respectively. Further, the rectangle and elliptical dielectric loading were investigated. Table 2 shows the performance comparison of the dielectric loading at 60 GHz. The dielectric loaded antenna was suggested in Ref. [27] which are useful in high gain applications. However, the dielectric loaded antenna using SIW technology provides slightly higher gain with wider main lobe directions at 60 GHz.

Table 2 Performance comparison of the dielectric loading at 60 GHz

Dielectric loading	Gain /dB	Main Lobe (Degree)	S_{11}/dB	VSWR	Side lobe /dB
Without	7.2	80	-12.07	1.66	-4.0
Rectangle	8.3	82	-11.43	1.73	-3.8
Elliptical	10.2	84	-12.23	1.64	-6.2

The simulated results of 3D radiation pattern, S_{11} parameter, and VSWR for the antenna with elliptical dielectric loading is shown in Figs. 5-7.

Compared with antenna without dielectric loading, the gain of the elliptically dielectric loaded antenna is increased by 3.0 dB, S_{11} parameter has decreased by -0.16 dB and main lobe direction is increased by 4 degree with less side lobe level. From these results it is seen that elliptical dielectric loading antenna gives higher gain with

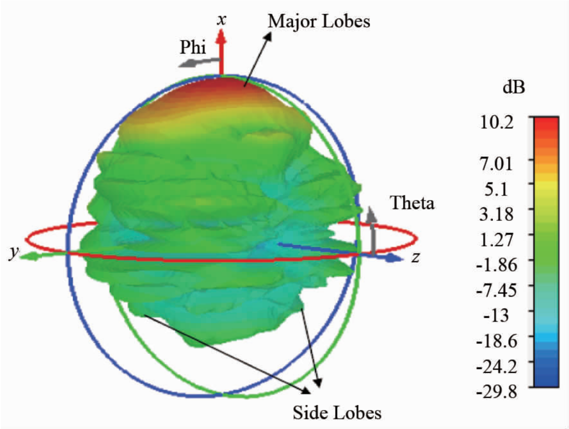

Fig. 5 Simulated 3D radiation pattern of antenna with elliptical dielectric loading

marginally broader main lobe direction at 60 GHz. Figures 8-10 prove the validation of the designed elliptically dielectric loaded antenna.

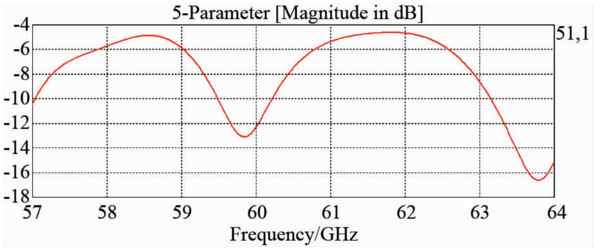

Fig. 6 Simulated S_{11} parameter of antenna with elliptical dielectric loading

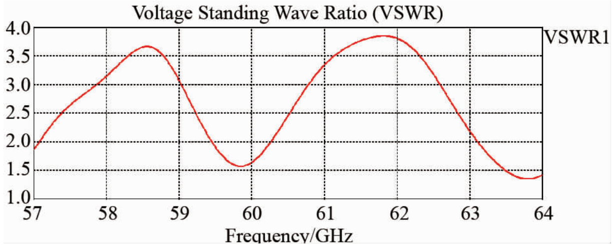

Fig. 7 Simulated VSWR of antenna with elliptical dielectric loading

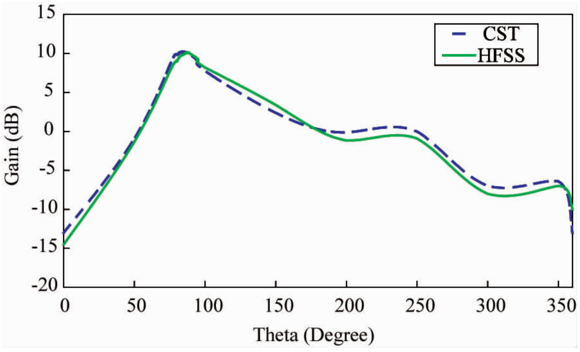

Fig. 8 Simulated gain comparison between CST and HFSS for antenna with elliptical dielectric loading

The performance comparison of antenna with elliptical dielectric loading using 3D electromagnetic software CST and comparisons with HFSS validate the design procedure based on antenna gain, S_{11} and VSWR. It is observed that there is good agreement in the simulated results between the gain, S_{11} and VSWR. A slight difference in the two simulated values is basically because of the two different numerical methods employed in CST and HFSS. Furthermore, the antenna radiation efficiency with elliptical dielectric loading is found to be 96.84% and total efficiency is 91.05%.

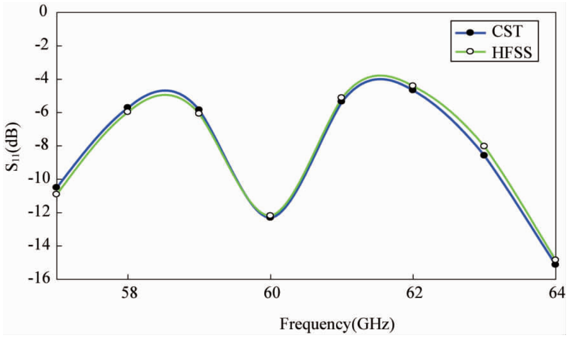

Fig. 9 Simulated S_{11} parameter comparison between CST and HFSS for antenna with elliptical dielectric loading

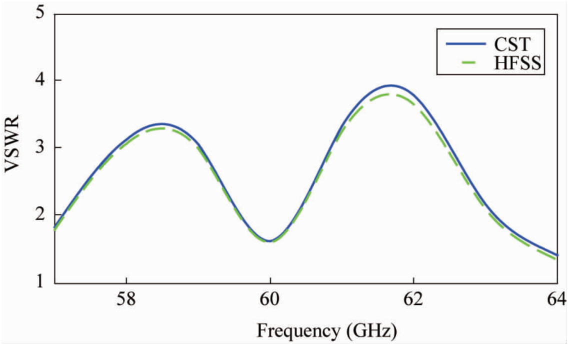

Fig. 10 Simulated VSWR comparison between CST and HFSS for antenna with elliptical dielectric loading

The antenna without dielectric loading and elliptical dielectric loading with optimized dimensions are fabricated on Rogers RT Duroid 5880 high frequency substrate with a thickness of 0.787 mm, relative permittivity of 2.2, relative permeability of 1, and loss tangent of 0.0009. The top side of the antenna having radiating flare and other side is ground plane. The photograph of the fabricated antenna without dielectric loading and elliptical dielectric loaded ETS antenna is shown in Fig. 11 and Fig. 12.

The elliptical dielectric loaded antenna simulated and measured results of S_{11} parameter, gain and radiation pattern are shown in Figs. 13-15. A slight difference is observed between the measured value and simulated one. The difference between the measured and simulated results of the antenna is caused by dielectric loss, connector loss and loss due to microstrip to SIW transition. Nevertheless, the results from simulation and measurement are in good agreement.

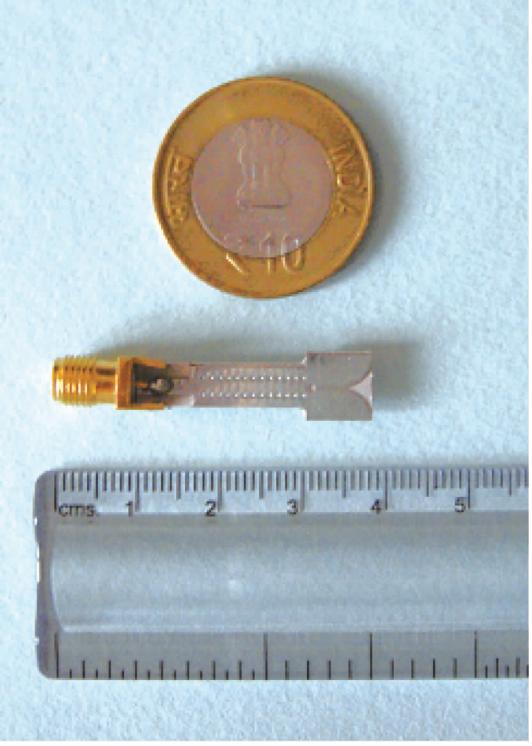

Fig. 11 ETS antenna without dielectric loading

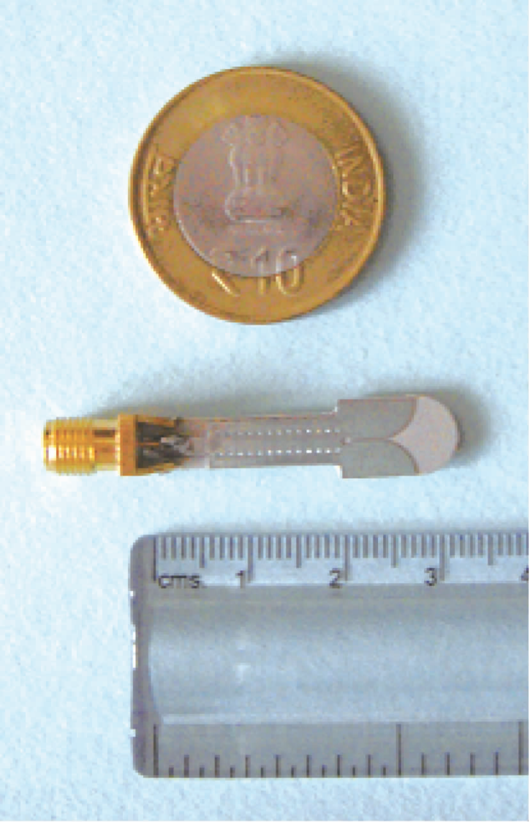

Fig. 12 ETS antenna with elliptical dielectric loading

2 1 × 4 Planar Dielectric Loaded ETS Antenna Array

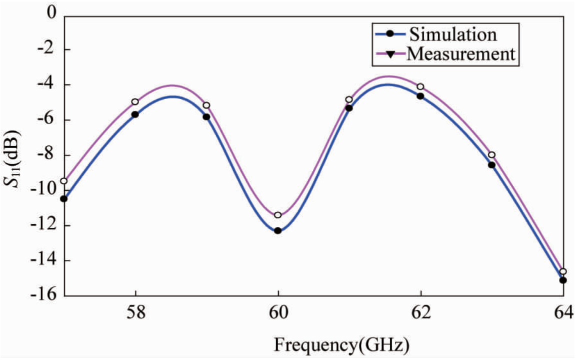

Fig. 13 Measured and simulated S_{11} parameter for antenna with elliptical dielectric loading

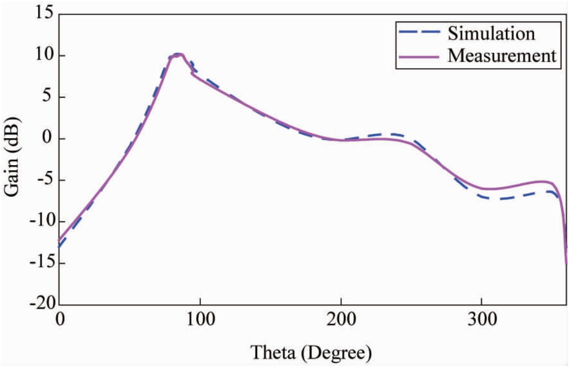

Fig. 14 Measured and simulated gain for antenna with elliptical dielectric loading

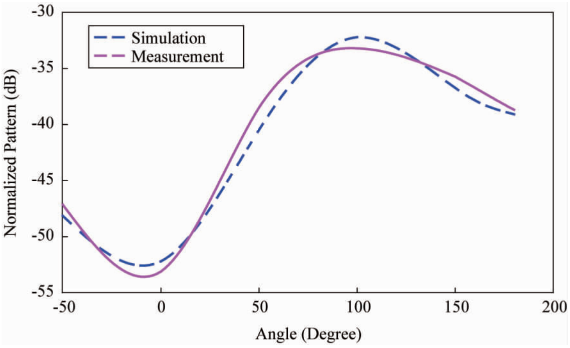

Fig. 15 Measured and simulated radiation pattern for antenna with elliptical dielectric loading

A Y- junction four way power divider was proposed to feed ETS array antenna. In the SIW Y-junction four way power divider, a metallic via as an inductive post, which is short circuited between two wide walls of the waveguide, is set to increase reflectance. Based on conventional waveguide transmission theory, the inductive post is equivalent to a parallel susceptance. Optimization of the inductive matching post diameter and position was performed in order to achieve a low return loss at 60 GHz. The Simulated S_{11} and S_{21} plots of the Y-junction four way power divider are shown in Fig. 16.

The ETS antenna array structure was fabricated in a single layer structure using Rogers RT Duroid 5880 with a thickness of 0.787 mm. Fig. 17 shows the photograph of the fabricated elliptically dielectric loaded ETS antenna array. The simulated and measured S_{11} and gain of the

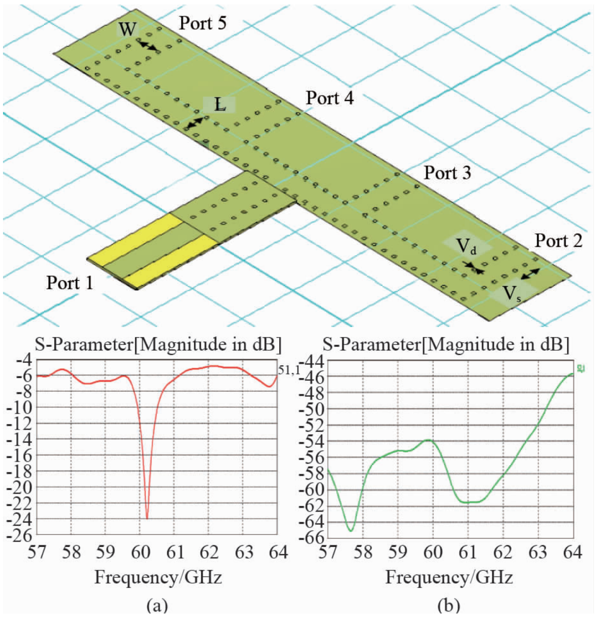

Fig. 16 (a) Geometry of power divider. (b) Simulated S_{11} and S_{21} of the Y-junction power divider
$W = 2$ mm, $L = 2$ mm, $V_d = 0.3$ mm, and $Vs = 0.7$ mm

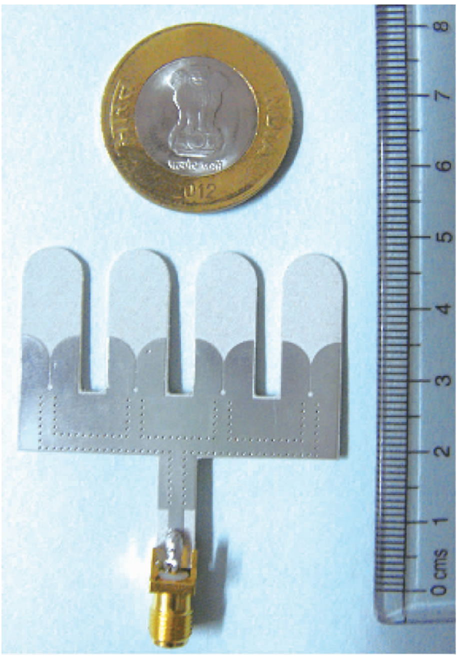

Fig. 17 Photograph of the fabricated ETS antenna array with elliptical dielectric loading

antenna array are shown in Fig. 18 and Fig. 19. When comparing simulated and measured S_{11} parameter of the antenna array, the simulation results show that much of the loss is caused by the dielectric loss effect at the feed network. The bandwidth of the antenna array covers the entire 60 GHz band, while the gain of the antenna is retained nearly constant within a wide bandwidth of the antenna array. The apparent difference between the simulated and measured gain might be due to the calibration related tolerance range of the antenna reference in the anechoic chamber.

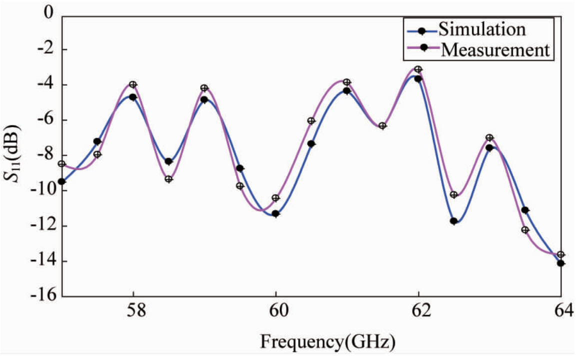

Fig. 18 Comparison of measured and simulated S_{11} parameter for elliptical dielectric loaded ETS antenna array

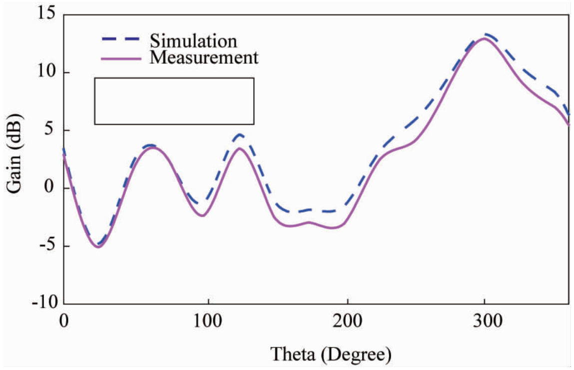

Fig. 19 Comparison of measured and simulated gain of elliptical dielectric loaded ETS antenna array

3 Conclusions

The use of MmW techniques offers many advantages for short-range gigabit wireless communication systems compared with radio techniques at lower frequencies. Besides, a new adaptation between microstrip line and SIW was proposed which is predominantly useful in MmW Gi-Fi wireless communication applications. The SIW technology with emulated waveguides can be utilized to eliminate the unwanted radiations from feed, particularly when compared with similar structures built using microstrip lines. A novel configuration of SIW based ETS antenna with dielectric loading was proposed, designed, fabricated and measured. The proposed antenna measured gain of the single element antenna is 10.2 dB, return loss is -12.23 dB, VSWR is 1.64 and main lobe direction is 84 degree. The gain of the 1 ×4 antenna array is 13.3 dB, return loss is -7.36 dB, VSWR is 1.89 and main lobe direction is 120 degree at 60 GHz. It was also observed that with proper selection of dielectric structures and its parameters, marginally more gain with broader main lobe direction for the given antenna can be achieved. The reasonable agreement between the simulated and measured results shows that the designed antenna with elliptical dielectric loading is useful for the variety of wireless applications.

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