Design and Optimization of Slotted Micro-Machined Patch Antenna Using Composite Substrate

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Abstract **─** A slotted L-shaped micro-machined patch antenna on composite substrate has been proposed in this article. The slotted patch has been designed on the composite substrate with overall height of 1.675 mm and effective dielectric constant of 3.23. The desired frequency and bandwidth has been achieved by the parametric optimization using Ant Lion optimization technique. The design resonates at 8.1 GHz and 13.5 GHz with the gain of 6 dBi. The simulated and measured results are quite promising. The obtained resonating characteristics of the proposed design are used in the earth exploration satellite services defined by ITU.

Index Terms **─** Ant Lion optimization, bandwidth, gain, micro-machining, satellite communications.

I. INTRODUCTION

As the requirement of the low power and small size wireless communication systems, it is desired to fabricate the complete module including oscillators, phase shifters, patch antenna and other circuitry on the single chip using monolithic microwave integrated circuit (MMIC) with improved performance parameters. This can only be achieved when patch antenna will be implemented on the high index substrate. To achieve high gain and bandwidth of the patch antenna designed on high index material, micromachining concept has been developed [1]. Performance characteristics of the patch antenna are highly influenced by the choice of the substrate. Although low refractive index substrate like roger and RT duroid shows the better performance than the high index materials like silicon and GaAs, this is due to the fact of low surface waves generation in case of low index materials rather than the high index materials. However, high index materials have their own advantages in terms of reduction in dimensions of the patch because the dimensions of the patch antenna are inversely proportional to the dielectric constant of the substrate. Moreover, the antennas designed on high index substrate are suitable for the MMIC designs. So, there is contrast between the performance parameters of the antennas implemented on the low and high dielectric constant substrate [2-3]. One solution is to use one substrate for the patch antenna, and another is for the other circuitry, but this would increase the overall cost of the system. So, from the above discussion it can be deduced that to design the patch on high index substrate for the integration on the single chip with superior performance characteristics, high index material is removed underneath the patch creating a low index environment under the patch and remain high index environment on all other section. The process of removal of the substrate underneath the patch is called bulk micromachining [4-5]. Micro-machining offers an alternative solution that satisfies all the requirements for both antenna and circuit. Further, to achieve the multiband characteristics current distribution plays a vital role which can be achieved by cutting the slot in the patch [6-9]. Previous work [10-15] reported the application of micromachining in various patch antennas for Ka band and Ku band. The 8.025-8.4 GHz band is used for earth exploration satellite services, the service is used in military operations, space agencies, commercial and many other organizations [16].

Bandwidth is the major drawback of the patch antenna, there are number of ways to improve the bandwidth represented in the literature [17-19]. One of the concepts is to increase the overall thickness of the substrate. So, the concept of composite substrate has been used in this paper. Further, to achieve the desired operating frequency and bandwidth of the patch antenna, Ant Lion optimization has been applied on the two-dimensional parameters of the antenna with composite substrate. First length of the micro-machined patch has been optimized to achieve the required operating frequency and then height of the composite substrate has been optimized to achieve the required bandwidth of operation.

II. MICRO-MACHINED PATCH ANTENNA

The idea of micro-machining has been driven from drilling the holes in conventional substrates like FR4

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or Duroid to improve the antenna performance characteristics [20]. There will be a reduction in effective dielectric constant with these holes near the patch; the same approach has been extended for the high index substrate. The shape of the micro-machined structure determined by the available etching processes, which include etching method, etching duration and crystal orientation of the substrate. In the process of Micro-machining, a portion of high index substrate has been removed underneath the patch to create the low index environment underneath the patch. This creates a cavity underneath the patch which consists of a mixed region of air and high dielectric substrate. In this work T = 655 μm of silicon substrate is removed of the total 675 μm thickness underneath the patch. Slanting positions of the walls of the cavity due to the anisotropic nature of the etching and the angle of slanting wall position is 54.7° as shown in Fig. 1.

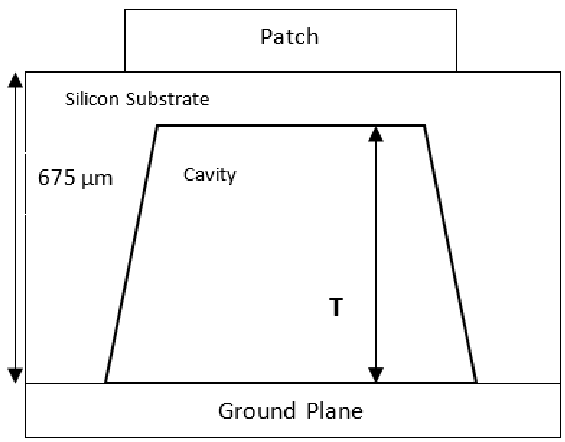

Fig. 1. Micro-machined patch antenna.

As shown in Fig. 1, there is a region of mixed air-silicon. The effective dielectric constant can be calculated by using cavity model. The capacitance of the patch in mixed region is given by [1,4]:

$$C = \frac{\varepsilon_{eff}\, A}{d}, \tag{1}$$

where C is the capacitance, A is the area of patch and d is the substrate thickness $\varepsilon_{eff} = \varepsilon_{reff}\varepsilon_o$. In this context, walls of the cavity assumed to be straight and ε_{reff} is estimated from following equations:

$$\varepsilon_{cavity} = \frac{\varepsilon_{air}\varepsilon_{sub}}{\varepsilon_{air}+(\varepsilon_{sub}-\varepsilon_{air})X_{air}}, \tag{2}$$

$$\frac{\varepsilon_{fringe}}{\varepsilon_{cavity}} = \frac{\varepsilon_{air}+(\varepsilon_{sub}-\varepsilon_{air})X_{air}}{\varepsilon_{air}+(\varepsilon_{sub}-\varepsilon_{air})X_{fringe}}, \tag{3}$$

$$\varepsilon_{reff} = \varepsilon_{\text{cavity}}\left(\frac{\text{L}+2\Delta\text{L}\frac{\varepsilon_{\text{fringe}}}{\varepsilon_{\text{Cavity}}}}{\text{L}+2\Delta\text{L}}\right). \tag{4}$$

In the above formula ε_{sub} is dielectric constant of substrate. ε_{air} is dielectric constant of air X_{air} the ratio of the air to full substrate thickness in the mixed field region and X_{fringe} the ratio of the air to full substrate thickness in the fringing field regions.

III. EFFECT OF COMPOSITE SUBSTRATE

Micro-strip patch antenna has several disadvantages like narrow bandwidth, low gain etc. Choice of the substrate material and height of the substrate have great impact on the performance characteristics of the patch antenna. Low permittivity substrates can increase the bandwidth at the cost of large dimensions and higher permittivity substrate will improve the quality factor hence the bandwidth reduces. The bandwidth is improved by micro-machining process in the high index substrates as explained in the above sections. Further improvement in the bandwidth of patch antenna can be achieved by using the concept of composite substrate [21]. The concept of composite substrate illustrates the insertion of the commonly available microwave substrate into the micro-machined designs, so the overall height of the substrate increases and bandwidth will improve. Also with the use of composite substrate resonant frequency of the microstrip patch can be shifted upward or downward without changing the actual patch dimensions. The choice of the substrate is based on the fact that low dielectric substrate lies below the patch and dielectric constant increases as we move towards the ground as shown in Fig. 2.

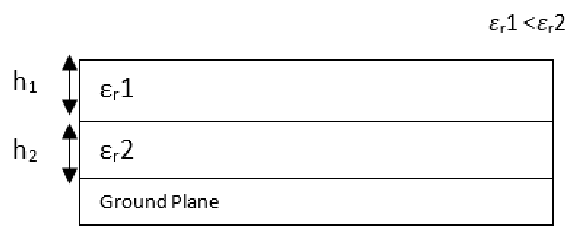

Fig. 2. Patch antenna on composite substrate.

The effective dielectric constant of both the layers has been recalculated by using equation (5) taking height of each substrate into consideration. The effective dielectric constant is calculated from equation (5) [21]:

$$\varepsilon_{rc} = \frac{h_1 + h_2}{\frac{h_1}{\varepsilon_r 1} + \frac{h_2}{\varepsilon_r 2}}, \tag{5}$$

where, ε_r1 is the dielectric constant and h_1 is the height of the low index substrate and ε_r2 is the dielectric constant and h_2 is the height of high index substrate.

IV. PROPOSED ANTENNA DESIGN

An L-shaped slotted patch antenna is designed on the composite substrate to achieve the multiband and wideband characteristics in X-band and Ku-band. Conventional rectangular patch antenna is designed on silicon substrate having dielectric constant of 11.8 of thickness 0.675 mm and loss tangent of 0.001. Due to the large surface wave generations in high index substrate micro-machined patch antenna has been designed with calculated effective dielectric constant from equation (4). Further to achieve the multiband characteristics, L-shape slot of effective length of 8mm and width of 1 mm has been cut from the patch and overall design has been implemented on the composite substrate, one is micro-machined silicon and other is glass substrate. The top view and side view of the proposed design has been shown in the Fig. 3 and Fig. 4 respectively.

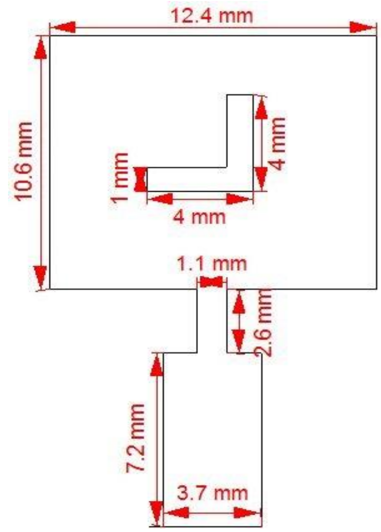

Fig. 3. Front view of L-shaped slotted patch antenna on composite substrate.

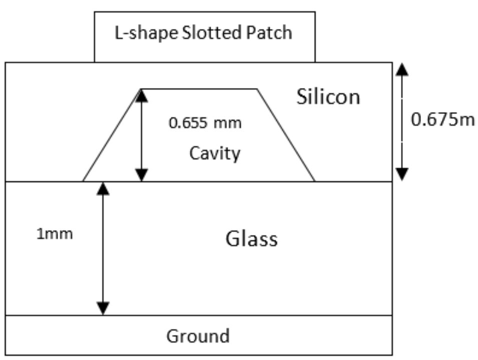

Fig. 4. Side view of slotted antenna on composite substrate.

The overall height of the substrate has been taken as 1.675 mm from which 0.675mm is for the micro-machined silicon substrate and 1mm for the glass substrate. The effective dielectric constant has been calculated from the equation (5). The calculated dimensions of the design have been shown in the Table 1.

Table 1: Dimensions of proposed design

	Conventional Rectangular Patch on Silicon Substrate	Rectangular Patch on Micro-Machined Silicon Substrate	L-shaped Slotted Patch on Composite Substrate of Micro-Machined and Glass
Effective dielectric constant	11.8	2.01	3.23
Overall height (mm)	0.675	0.655 mm cavity from 0.675 mm	1.675
L (mm)	4.94	12.76	10.6141
W (mm)	7.23	14.64	12.418
W_{qw} (mm)	0.023	0.11	1.14
L_{qw} (mm)	2.62	2.62	2.66
W_f (mm)	0.588	0.588	3.7
L_f (mm)	3.88	3.88	7.23

V. IMPLEMENTATION OF ANT LION OPTIMIZATION

Ant Lion optimization has been implemented to find the certain optimized dimensional parameter to achieve the required performance parameters.

A. Concept of Ant Lion optimization

Ant Lion optimization (ALO) is executed to achieve optimized rectangular patch. In its execution, an antlion builds a sharp edged cone structure under the soil and waits for the prey. When the respective prey (ant) slips into the hole, the prey tries to come out of the hole and antlion throws sand on to the prey. This process is repeated until the respective prey gets exhausted in its action. Ultimately, antlion consumes the body of the exhausted prey. After that antlion builds another hole and the process repeats again and again [22-23]. It is supposed that fitness of the Ant should be more than the fitness of the corresponding Ant Lion, then and only then Ant Lion consumes body of the ant. An Ant Lion updates its position to catch other ant. This process is imitated using the equation (6) proposed in the work at [24]:

$$Antlion_k^i = Ant_k^i$$
If
$$Fitness(Ant_k^i) > fitness(Antlion_k^i). \tag{6}$$

Where, $Antlion_k^i$ is the position of k-th antlion in i-th iteration and Ant_k^i shows the position of k-th ant at i-th iteration. In all the iterations fittest antlion produced is called elite. Due to this elite, the movement of all the ants have been altered during each iteration. Therefore, every ant updates their position according to the equation (7) reported in the work at [24]:

$$Ant = (Roulette\ wheel\ selection\ random\ walk\ selection)/2. \tag{7}$$

Ant-Lion optimization is better than particle swarm optimization, Genetic algorithm and other algorithms in terms of average value and the standard deviation of the fitness function [24]. The purpose of the algorithm is to find the minimum value of the fitness function to find the user defined frequency and bandwidth.

B. Optimization of patch length to find the required resonant frequency

From the calculated parameters as shown in Table 1. the length of the patch is 9.2 mm with total thickness of substrate is 1.675mm. Based on these calculations, the resonant frequency has been found to be 9 GHz. But required band is 8.025 to 8.4 GHz. So to obtain this operating band the length of the patch has to be optimized by using Ant Lion optimization. The polynomial equation has been formed from the curve fitting method:

$$Frequency = -0.8835 \times L^5 + 43.685 \times L^4 - 863.41L^3 + 8526.7L^2 - 42075L + 83001.6, \quad (8)$$

$$FitnessFunction = (8.3 - f)^2. \quad (9)$$

The above fitness function has been optimized using Ant Lion optimization and the optimized value of the length of the patch is 10.6142 mm at which the resonance frequency is 8.3 GHz as shown in Fig. 5.

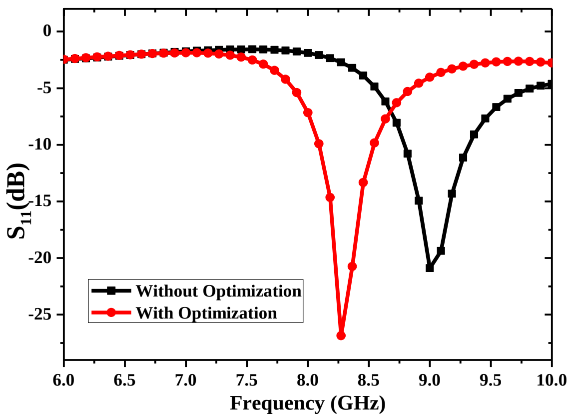

Fig. 5. Resonant frequency v/s Reflection Coefficient variation with and without optimization.

C. Optimization of the height of glass substrate to find the required operating band

For the Earth Exploration Satellite Service, the minimum required bandwidth of the patch antenna is 375 MHz (8.025-8.4 GHz). Bandwidth of the patch antenna depends upon the height of the substrate. So, in this section, required operating band can be achieved with the variation of the height of the glass substrate. The polynomial equation has been formed between the height of the glass substrate and bandwidth:

$$BW = 1960H_g^3 - 4906H_g^2 + 4253H_g - 859. \quad (10)$$

$$FitneesFunction = (375 - H_g)^2. \quad (11)$$

As the height of the substrate goes on increasing, the reflection coefficient and bandwidth improves. So the glass material with height 1 mm has been chosen due to large bandwidth and improved reflection coefficient. Fig. 6 shows the comparison between the micro-machined patch antenna and with sandwiching composite substrate underneath the micro-machined patch antenna, which illustrates the significant improvement in the bandwidth in case of micro-machined with composite substrate design over conventional micro-machined patch antenna design.

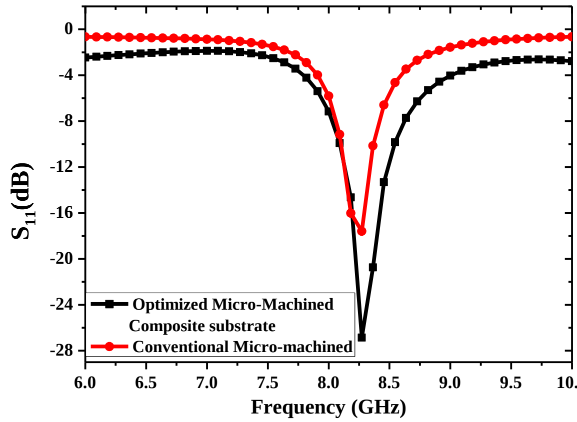

Fig. 6. Bandwidth variation of conventional micro-machined and optimized composite substrate structure.

VI. RESULTS AND DISCUSSIONS

The proposed antenna has been simulated using High Frequency Structure Simulator (HFSS 14.0) and measured results have been validated with Anritsu VNA master and Anritsu MS2719B spectrum analyzer. The fabricated prototype and the measurement setup have been shown in the Fig. 7 & Fig. 8 respectively. The simulated and measured resonant characteristics of the L-shaped slotted micro-machined patch antenna on composite substrates has been shown in Fig. 9. It has been seen that antenna resonates in X-band and Ku-band. In X-band it resonates at 8.1 GHz with a 5.3% impedance bandwidth and in Ku-band it resonates at 13.5 GHz with wideband characteristics of 30.3 % bandwidth. Further, radiation patterns have been measured in the anechoic chamber and simulated and measured radiation pattern for both frequencies have been shown in the Fig. 10 & Fig. 11. Figure 12 shows the gain v/s frequency graph which shows gain of 6.2 dBi at 8.1 GHz and 6.3 dBi at 13.5 GHz.

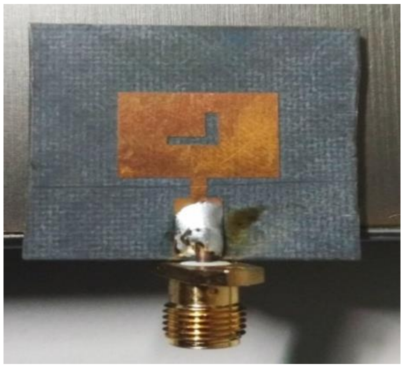

Fig. 7. Fabricated prototype of slotted micro-machined patch antenna.

Fig. 8. Antenna mounted in anechoic chamber.

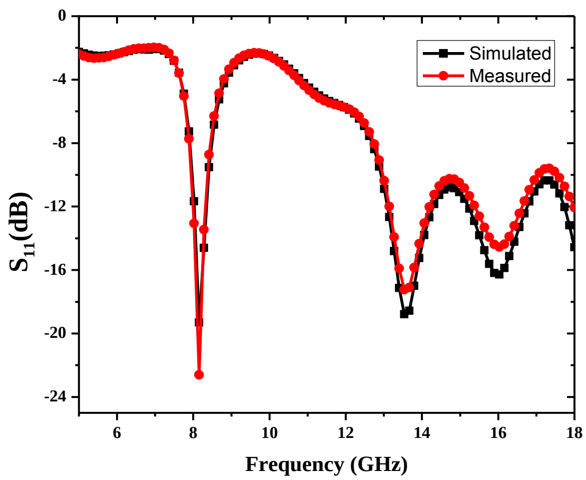

Fig. 9. Reflection coefficient v/s frequency curve of slotted micro-machined patch antenna.

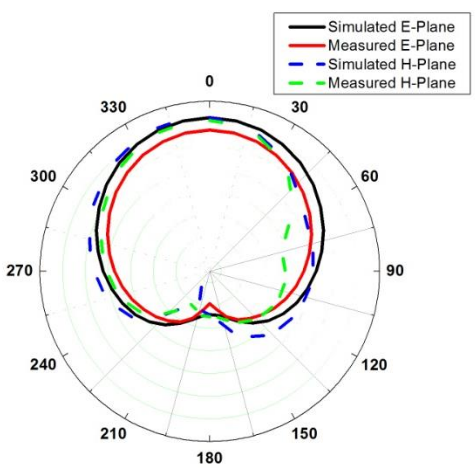

Fig. 10. Radiation pattern of slotted micro-machined patch antenna at 8.15 GHz.

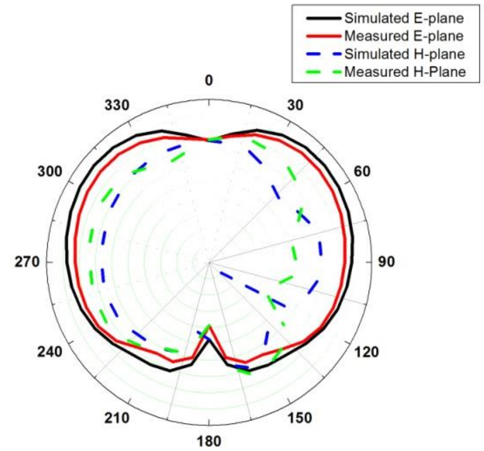

Fig. 11. Radiation pattern of slotted micro-machined patch antenna at 13.5 GHz.

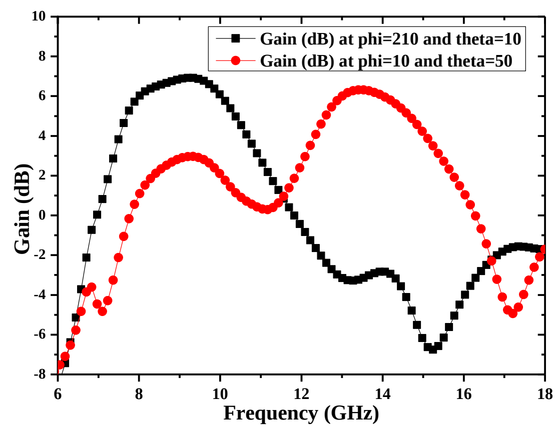

Fig. 12. Gain v/s frequency of slotted micro-machined patch antenna.

Table 2: Performance parameters

	Conventional Rectangular Silicon Substrate	Rectangular Micro-Machined Silicon Substrate	L-shaped Slotted Patch on Composite Substrate of Micro-Machined and Glass	
Resonant freq. (GHz)	8.3	8.3	8.15	13.5
Reflection coefficient (dB)	-15.5	-17.6	-22.6	-17
Bandwidth (MHz)	197	266	434	4.1 GHz
Fractional bandwdith	2.3%	3.2%	5.3%	30.3%
Gain (dBi)	0.8 at θ=12° and Φ = 230°	6.6 at θ=0° and Φ = 270°	6.2 at θ=10° and Φ = 270°	6.3 at θ=50° and Φ = 10°

VII. CONCLUSION

L-shaped slotted patch antenna is designed on the composite substrate. The patch antenna design has been implemented on the micro-machined substrate combined with the glass substrate to increase the overall height of the substrate. The proposed design resonates at 8.1 GHz and 13.5 GHz with a 6 dBi gain. There is an improvement of 38% in the bandwidth over the conventional rectangular micro-machined patch antenna design, which can be used in various X-band and Ku-band applications like earth exploration satellite services.

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