ISSN 1726-5749

SENSORS & TRANSDUCERS

9/07 vol. 83

TEDS Sensors, IEEE 1451 Standards

International Frequency Sensor Association Publishing

IFSA

Sensors & Transducers

Volume 83
Issue 9
September 2007

www.sensorsportal.com

ISSN 1726-5479

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Sensors & Transducers Journal

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Volume 83
Issue 9
September 2007

www.sensorsportal.com

ISSN 1726-5479

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Sensors & Transducers Journal, Vol.83, Issue 9, September 2007, pp. 1564-1573

Sensors & Transducers

ISSN 1726-5479

http://www.sensorsportal.com

Performance Enhancement of the Patch Antennas Applying Micromachining Technology

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Received: 1 July 2007 /Accepted: 17 September 2007 /Published: 24 September 2007

Abstract: This paper reports on the application of micromachining technology for performance enhancement of two types of compact antennas which are becoming a common practice in microsystems. Shorted patch antennas (SPA) and folded shorted patch antennas operating in the 5-6 GHz ISM band, with intended application in short-range wireless communications, are considered. The electrical length of antennas are modified by etching the substrate of the antennas, thus providing a new degree of freedom to control the antenna operating properties, which is the main novelty of our work. The gain and bandwidth of the antennas are increased by increasing the etching depth. However, etching the substrate affects the operating frequency as well. To keep the operating frequency at a pre-specified value, the dimension of the antennas must be increased by deepening the etching depth. Therefore, a trade off between the performance enhancement of the antennas and the dimensional enlargement is required. *Copyright © 2007 IFSA.*

Keywords: Shorted patch antenna, Folded shorted patch antenna, Micromachining, Wireless microsystems

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1. Introduction

Distributed systems equipped with short-range wireless communication capabilities will highly be facilitated if cheap and easy-to-use 'on-chip' or 'in-package' solutions would be available. The antenna is the key element in order to fully integrate a wireless Microsystems in a single chip. The necessary on-chip integrated transceivers, from baseband to antenna input/output, are already available, where short-range wireless communication systems operating in the 5-6 GHz ISM band play an important role in the actual communication standards. However, the antenna, as the key element in achieving a fully integrated solution, notwithstanding all the development efforts, still remains to be an open challenge. Full integration requires the availability of very-small antennas that can be fitted into a single chip. Several small and planar antenna types have been proposed for wireless communications [1] but none of them was designed to fulfill all the restrictions and requirements set by on-chip integration. Those restrictions include the properties of available substrate materials and the way they can be processed. Many of the previously proposed solutions to integrate antennas on-chip have been based on the design of planar antennas using silicon as substrate [2]. In this way, a preferable solution to decrease the antenna losses may be to use a combination of air as a low-loss material, and silicon as the well suited material for micromachining technology [3]. As we have reported before, micromachining technology can be employed for fabricating some RF devices [4, 5]. Cavities in silicon substrates can be easily implemented using micromachining technology and a partial ratio of air and silicon may be obtained. Applying this ratio, electrical properties for different antenna substrate can be extracted. Employing micromachining technique allows reduction of the losses, increase of gain and bandwidth at the expense of increased antenna dimension. Therefore, advanced antenna architectures are required to overcome this drawback. Our work, presents micromachined patch antennas as a method to overcome to some part of the problem. The behavior of the proposed antennas is investigated before and after substrate etching. Using our obtained results, one may arrive to a trade off between the shorted patch antenna performance and its dimension.

2. Theoretical Analysis

The proposed patch antennas are designed to operate at the frequency of 5.7 GHz, a frequency chosen to be inside the 5-6 GHz ISM band. The design is based on the knowledge that the operating frequency can be adjusted by proper selection of the antenna size and middle patch length, or changing the substrate thickness [6]. The folded SPA antenna is formed by three horizontal metal sheets that are electrically connected by vertical metal vias. Fig. 1 shows the cross section of the proposed double-slotted folded-patch antenna. The SPA antenna structure is similar to the folded SPA leaving out the second stacked patch.

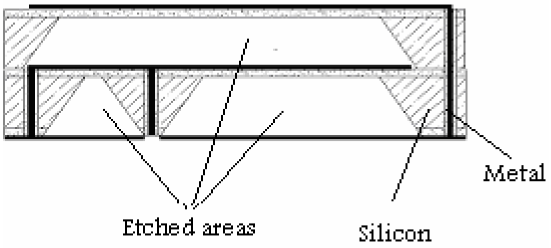

Fig.1 Cross section of the folded SPA antennas.

The effective dielectric constant of the mixed air-silicon patch substrate can be calculated using the quasi-static capacitor model presented by Papapolymerou [2]. Equation (1) provides an accurate result as long as the cavity is large enough to accommodate the fringing fields of the patch.

$$\varepsilon_{cavity} = \frac{\varepsilon_{air}\varepsilon_{Si}}{\varepsilon_{air} + (\varepsilon_{Si} + \varepsilon_{air})\chi_{air}}, \tag{1}$$

where, X_{air} is the ratio of air to full substrate thickness.

As is the case for microstrip transmission lines, an equivalent dielectric constant ε_{reff} needs to be calculated. This equivalent constant is used to replace the substrate and the surrounding air with a fictitious homogeneous material. The impedance performance of the folded SPA antenna can be analyzed by employing a simple transmission-line model. The standard SPA can be represented by a transmission-line equivalent circuit as shown in Fig.2. Assuming upper patch as a plate along the lower patch, as shown in Fig.1, the input impedance of folded SPA antennas is similar to the standard SPA (Fig.3) and it can be obtained from:

$$Z_{in} = jX_f + Z_1, \tag{2}$$

where, X_f is the feed-probe reactance and is given by [7]:

$$X_f = \frac{\omega\mu_0 h}{2\pi}[\ln(\frac{2}{\beta * r_p}) - 0.57721], \tag{3}$$

with $\beta = 2\pi / \lambda_0$ and r_p is the feed-probe radius. Z_1 (= 1/Y1) is obtained from the transmission-line equivalent circuit, that is:

$$Y_1 = Y_{01}\frac{1}{j\tan(\beta Y_p)} + Y_{01}\frac{Y_2 + jY_{01}\tan[\beta(l_1 - y_p)]}{Y_{01} + jY_2\tan[\beta(l_1 - y_p)]} \tag{4}$$

and:

$$Y_2 = Y_{02}\frac{Y_s + jY_{02}\tan(\beta l_1)}{Y_{02} + jY_s\tan(\beta l_1)}, \tag{5}$$

where, Y_{01} and Y_{02} are the characteristic admittances of the lower and upper patches respectively.

In our calculations, we used the following equations for Y_0 = (Y_{01} for h = h1 or Y_{02} for h = h2) and:

$$Y_s = G_s + jB_s, \tag{6}$$

where, G_s is the conductance associated with the power radiated from the radiating edge (or the radiating slot), and B_s is the susceptance due to the energy stored in the fringing field near the edge.

In our calculations, we used the following equations for Y_0, G_s, and B_s:

$$Y_0 = \frac{W/h + 1.393 + 0.667\ln(W/h + 1.444)}{120\pi} \quad \text{for } W/h \geq 1 \tag{7}$$

and

$$G_s = \begin{cases} W^2/(90\lambda_0^2) & for \quad W \leq 0.35\lambda_0 \\ W/(120\lambda_0) - 1/(60\lambda_0^2) & for \quad 0.35\lambda_0 \leq W \leq 2\lambda_0 \\ W/(120\lambda_0^2) & for \quad 2\lambda_0 \leq W \end{cases} \tag{8}$$

$$B_s = Y_{02} \tan(\beta \Delta l). \qquad (9)$$

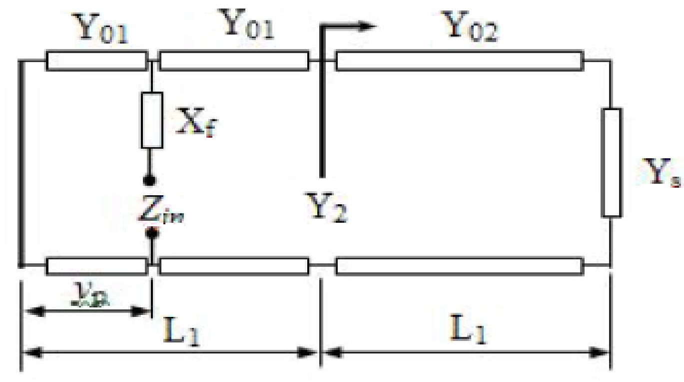

Fig.2. Folded SPA and its equivalent transmission-line model.

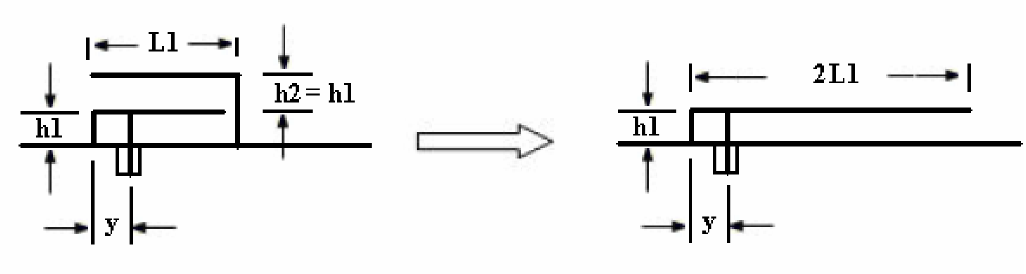

Fig.3. Equivalency of folded SPA and standard SPA.

3. Simulations and Results

The proposed antenna structures are simulated employing the high frequency structure simulator (HFSS) software. The simulation starts with the antenna structure of no etched cavity. As it has already been mentioned, the etching depth of substrate is a parameter which can affect the performance of antenna. In our work the distance between the ground plane and the lower patch is considered as h1=500 μm, the thickness of a standard four inches silicon wafer. The distance between the lower patch and the upper patch is also considered h2=500 μm. It is clear that this thickness for standard SPA is only h1=500 μm. Seven different etch depths between 0 and 500 μm were considered for simulation purpose and the effect of each one on the antenna performance was investigated. The obtained results verify that the application of micromachining technique is an effective way to modify the gain and bandwidth of the antennas. The calculated results for input impedance variation versus etch depth were in a close agreement with the simulated results.

Fig.4 shows the simulated 3D radiation pattern of standard SPA.

The simulated results for the gain variation versus etched depth are shown in Fig. 5 and 6 for short patch and folded SPA respectively. The gain is increased for deeper substrate etching in both cases. However, there is no linear relationship between them. The nonlinearity is more pronounced for the case of folded short patch antenna. Smith charts indicating the effect of etching depth on input impedance are shown in Fig. 7 and 8 for shorted patch and folded shorted patch antennas respectively.

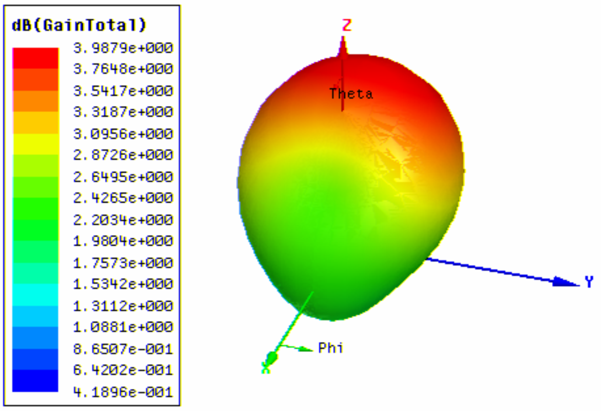

Fig.4. 3D radiation pattern of shorted patch antenna h=350µm depth etching.

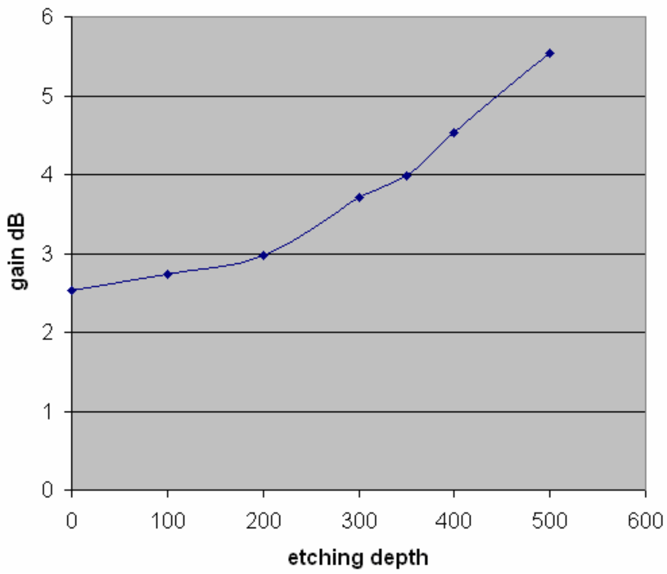

Fig.5. Effect of etch depth on the gain of shorted patch antenna gain.

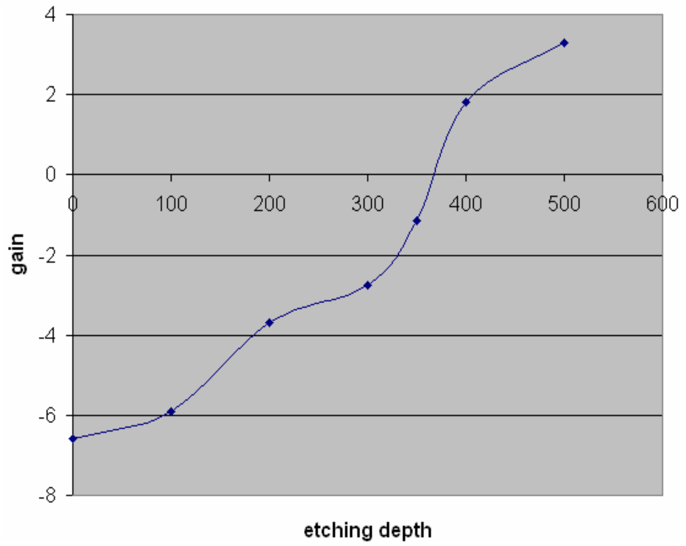

Fig.6. Effect of etched depth on the gain of folded short patch antenna gain.

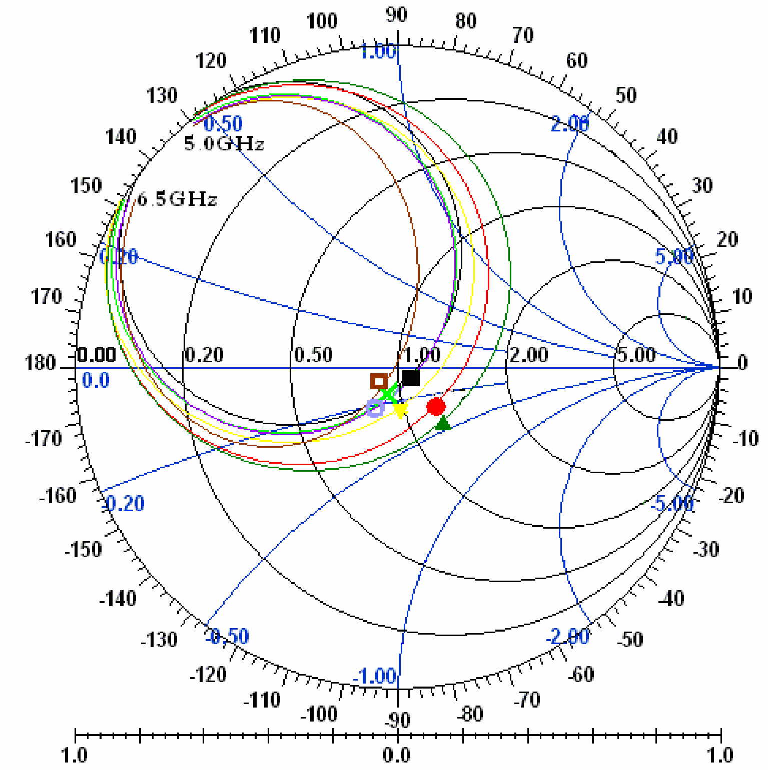

Fig. 7. Smith chart of input impedance versus frequency for shorted patch antenna for different values of etching depth.

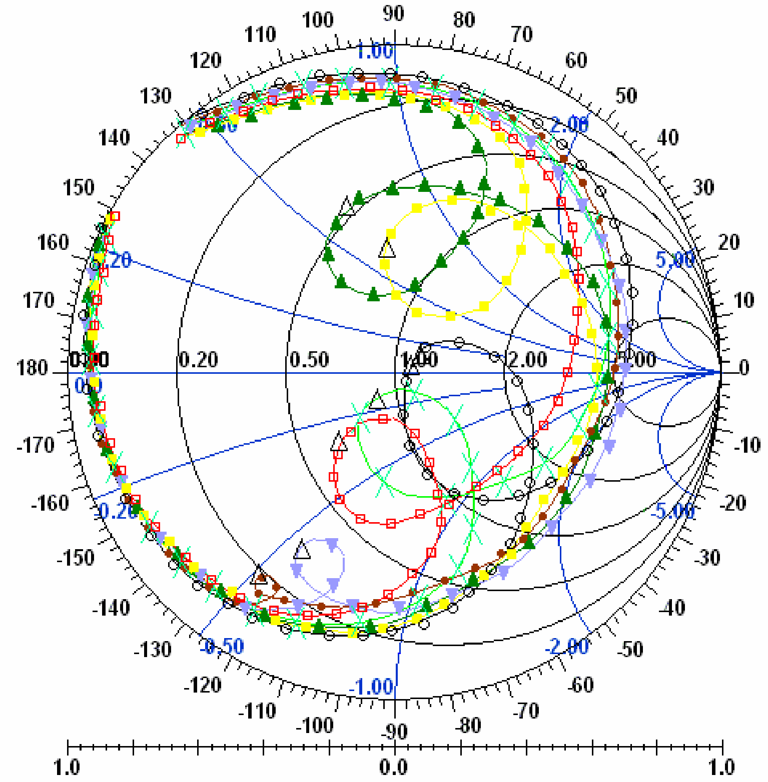

Fig. 8. Smith chart of input impedance versus frequency for folded shorted patch antenna for different values of etching depth.

The obtained simulated results of the input impedance variation versus etching depth are compared with the calculated analytical results. Tables 1 and 2 show the tabulated comparisons of the simulation and analysis results for shorted patch and folded shorted patch antennas respectively. The theoretical and simulated results for input impedance are in a good agreement, differing with less than 5 % for shorted and less than 10 % for folded shorted patch antennas.

Table 1. Comparison of theoretical and simulations results for input impedance of standard SPA.

Etching depth	Numerical analysis SPA Zin	Simulations SPA Zin	Error %
Without etch	1.19-j0.15	1.25-j0.099	5.041
100µm	1.084-j0.11	1.15-j0.073	6.08
200µm	1.04-j0.076	1.09-j0.069	4.8
300µm	0.94-j0.071	0.98-j0.058	4.25
350µm	1	1.04-j0.001	4
400µm	0.87-j0.054	0.83-j0.012	4.59
500µm	0.91-j0.019	0.87-j0.008	4.39

Table 2. Comparison of theoretical and simulations results for input impedance of folded SPA.

Etching depth	Numerical analysis Folded SPA	Simulations Folded SPA	Error %
Without etch	0.664-j0.65	0.638-j0.79	3.91
100µm	0.756-j0. 8	0.73-j0.61	3.43
200µm	0.87-j0.29	0.832-j0.37	4.36
300µm	0.964-j0.18	0.918-j0.11	4.77
350µm	1	1.062+j0.017	6.2
400µm	0.952+j0.21	0.874+j0.31	8.19
500µm	0.836+j0.4	0.918+j0.47	9.8

The effect of the etching on the bandwidth was also investigated for the antennas. The simulated results are shown in Fig. 9 and 10 for standard SPA and folded SPA respectively, where the relative -10 dB return loss bandwidth (normalized to the resonant frequency f_r) is plotted as a function of the etching depth. It is evident from the Fig. 9 and 10 that the bandwidth increases as the etched depth is increased.

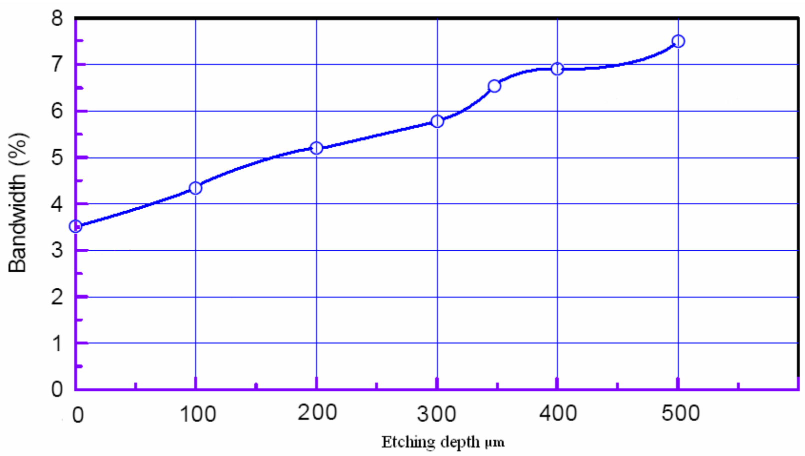

Fig. 9. Bandwidth of shorted patch antenna versus etching depth.

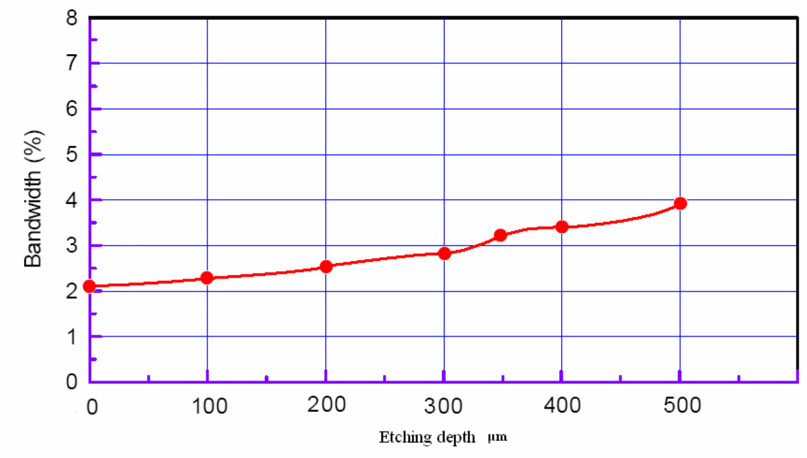

Fig. 10. Bandwidth of simulated folded SPA versus etching depth.

The main drawback of this technique is that the substrate etching shifts the operating frequency. To keep a constant operating frequency for different substrate etching depth, the size of the antennas must be modified. In our case, to fix the frequency at 5.7 GHz, the required variation on the antenna dimensions are shown in Fig. 11 and 12 for shorted patch and folded shorted patch antennas respectively. According to these figures, to have a fixed operating frequency for deeper substrate etching depths, the dimensions of the antennas must be increased dramatically. However, according to Fig. 5, 6, 9 and 10, the advantages of substrate etching are increased gain and bandwidth for both types of the antennas. Therefore, for a specified fixed operation frequency, there is a limitation on the choice of gain, bandwidth and the antennas dimension.

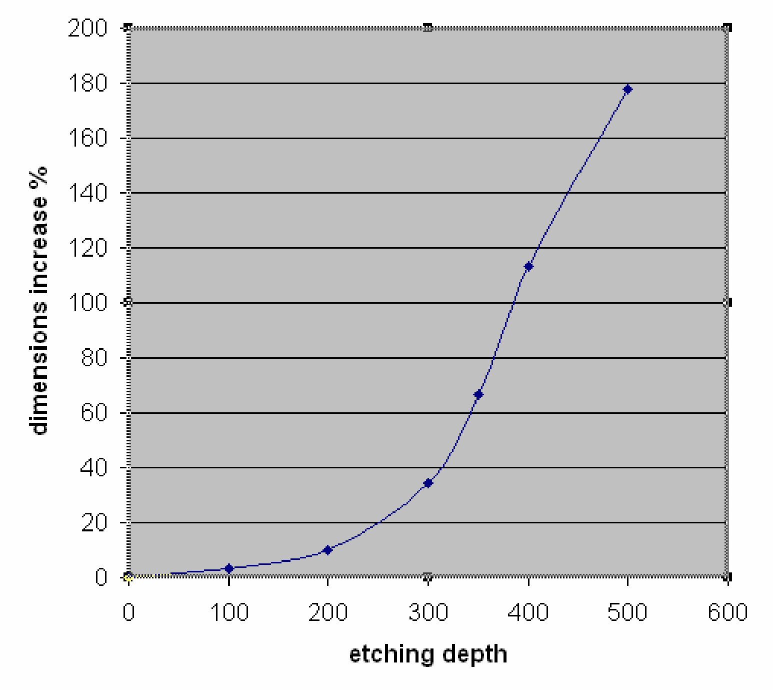

Fig.11. Antenna dimensions variation for SPA versus etching depth.

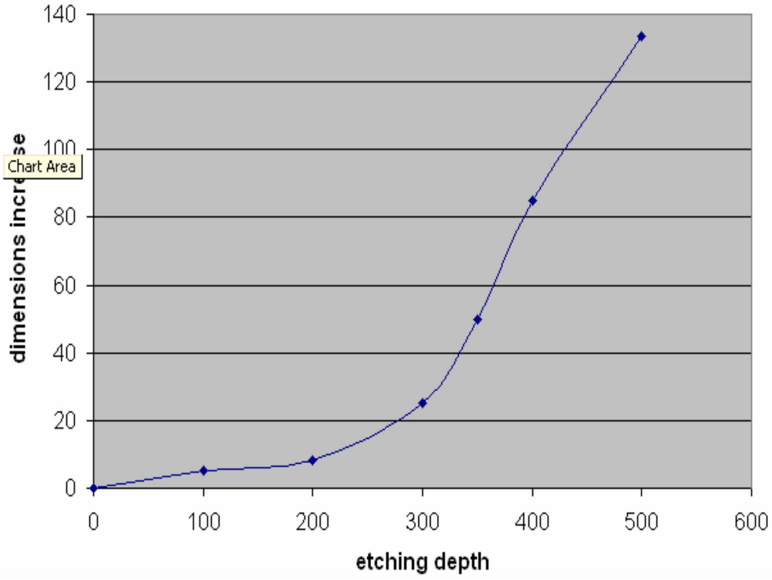

Fig.12. Antenna dimensions variation for folded SPA versus etching depth.

4. Conclusion

A new method for the gain and bandwidth control of the shorted patch antennas and folded shorted patch antennas operating at the 5-6 GHz ISM band is presented. The method is based on the etching of antennas substrate using the well established micromachining technique. The effect of substrate etching on the operating frequency and the input impedance has also been investigated. To keep the operating frequency at a pre-specified value, the dimension of the antennas must be modified depending on the substrate etch depth. Since the dimension of the antennas increases with etching depth, a compromise between the antennas gain or bandwidth and dimension is required.

Acknowledgement

The authors would like to thank the Iranian telecommunication research center (ITRC) for the financial support of the project.

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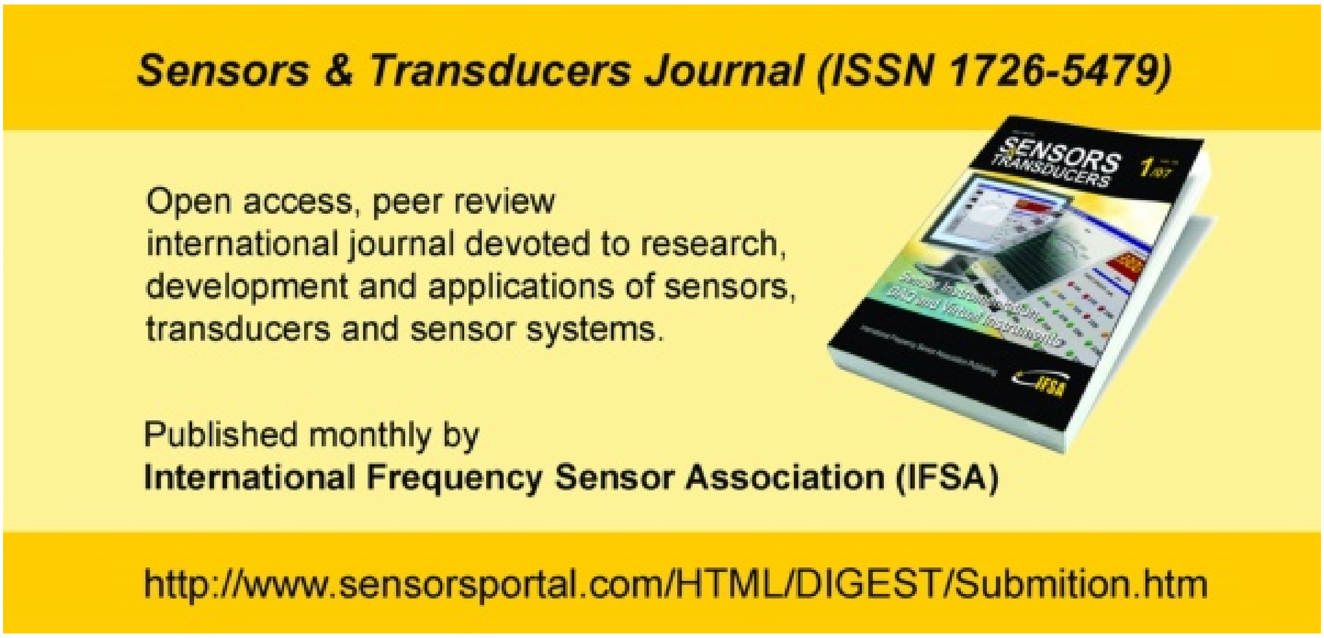

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