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Mechanically Frequency Reconfigurable Antenna and its Application as a Fluid Level Detector for Wireless Sensor Networks

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Abstract

A mechanical frequency reconfiguration technique in microstrip patch antennas for wireless sensor networks is presented in this paper. Frequency reconfiguration is achieved by mechanically changing the dielectric properties of the antenna and thereby obtaining a tunable frequency range from 2442 MHz to 2716 MHz. The gain of the prototype remains relatively flat throughout the reconfigured frequency range with a stable radiation pattern. The prototype is then studied as a fluid level sensor which operates based on the variation in resonant frequency with the rise or fall of the fluid in the dedicated channels engraved. The antenna is able to sense and transmit the information simultaneously with reduced complexity and less power consumption. Thus the proposed antenna could be used a fast wireless sensor for remote fluid level monitoring in wireless sensor networks.

1 Introduction

Modern wireless communication systems include antennas that are versatile in terms of operating frequency, gain, polarization, radiation pattern etc. One of the significant aspect of such antenna systems is that they are required to be compact and less complicated besides being low on power consumption. These requirements have paved the way for an extensive research on reconfigurable antennas. Reconfiguration, here, means modifying a certain aspect of an antenna as per the desired output. That aspect could be the radiation pattern or the polarization or the operating frequency of the antenna or a combination of these parameters. Reconfigurable antennas allow modern wireless systems to exhibit a variety of different radiation characteristics while making use of a single antenna system.

Frequency reconfigurable antennas (FRA) modify the operating frequency of the antenna by electrical, optical or mechanical means. FRA employing electrical switching mechanism alters the effective dimension of the radiating element using PIN diodes, varactor diodes, MEMS switches, RF switches etc [1, 2]. Optical method involves the use of photoconductive materials acting as switches as demonstrated in [3]. Mechanically frequency reconfigurable antennas make use of stepper motors to change the geometry of the radiating element thereby changing its operating frequency [4]. This type of reconfiguration technique is far less explored as compared to its couterparts. However, mechanical FRAs could be used in Wireless Sensor Networks (WSN) which have found a lot of scope in Internet of Things (IoT) systems. Usually, the output information from WSN sensors is transmitted to the relevant location with the help of an antenna [5]. The combined weight of the sensor and the antenna can lead to a bulky system.

A frequency reconfigurable antenna system that alters the radiation characteristics by changing the dielectric property of the substrate through mechanical means is presented in this paper. The system consists of a rectangular patch antenna on FR4 substrate of thickness 3.2 mm. The prototype shows a significant variation in the resonant frequency with the alterations in the substrate composition. Moreover, it is proved that the prototype could be used as a fluid level sensor whose working principle is elaborated in the paper.

2 Antenna Design

The microstrip patch antenna is designed to operate at 2442 MHz. The resonant frequency of the patch is related to the effective dielectric constant of the substrate as [6]:

$$f_r = \frac{c}{2L_{eff}\sqrt{\varepsilon_{eff}}} \tag{1}$$

where c is the velocity of light in free space, f_r is the resonant frequency, L_{eff} is the effective length of the patch antenna and ε_{eff} is the effective dielectric constant of the substrate. In the present study, ε_{eff} is varied which leads to a shift in the resonant frequency, thereby achieving frequency reconfiguration. Three cavities of optimized dimensions are engraved in the substrate which are oriented perpendicular to the microstrip feed line. The location and the placement of the cavities are optimized for better accuracy. With the inclusion of the aforementioned cavities, the radiation characteristics of the proposed antenna are illustrated in two different ways.

First, dielectric strips of FR4 are inserted in the cavities individually or in combination to achieve a a discrete

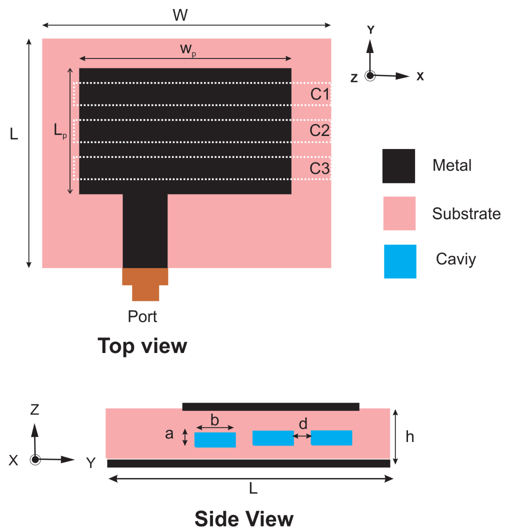

Figure 1. Geometry of the proposed antenna; Configuration 1
($L = 31$ mm, $W = 39$ mm, $L_p = 17$ mm, $W_p = 28$ mm, $h = 3.2$ mm, $a = 1.2$ mm, $b = 3$ mm and $d = 2$ mm)

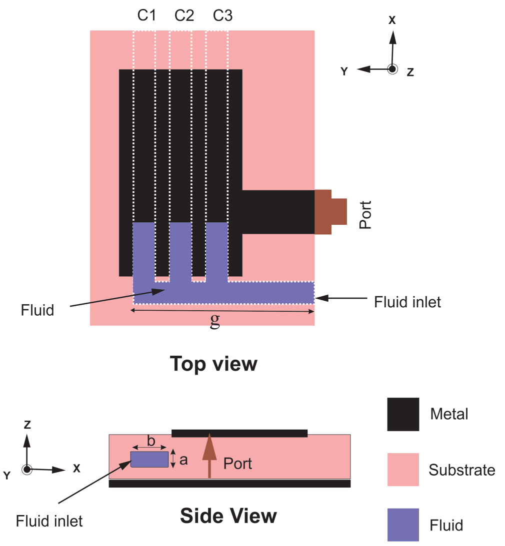

Figure 2. Geometry of the proposed antenna; Configuration 2
($g = 19$ mm, $a = 1.2$ mm and $b = 3$ mm)

frequency response. The geometry of the prototype with three cavities $C1$, $C2$ and $C3$ is shown in Figure 1. This particular configuration is presented for the proof of above mentioned concept. Second, the cavities are made to be partially or fully filled with a liquid, as shown in Figure 2, whose rise or fall leads to a change in ε_{eff} and hence the resonant frequency. The fluid used in this study in diesel with dielectric constant 2.1 [7].

3 Results and Discussions

The reflection characteristics and radiation pattern of the proposed antenna with and without the inclusion of cavities are shown in Figure 3 and Figure 4. The rectangular microstrip patch antenna resonates at 2442 MHz with 2:1 VSWR impedance bandwidth of 90 MHz (2400 MHz-2490 MHz) covering the entire WLAN band (2400 MHz-2480 MHz). The resonant frequency shifts to 2716 MHz with the inclusion of cavities. The proposed antenna shows a maximum gain of 3.22 dBi and 4.39 dBi along boresight direction at 2442 MHz and 2716 MHz respectively. There is no discernible change in radiation pattern. The two different applications of the aforementioned antenna are discussed in the following sections.

3.1 Mechanical Frequency Reconfiguration

The frequency reconfiguration is achieved by inserting dielectric strips inside the cavities $C1$, $C2$ and $C3$. The strips have the same dimension as that of the cavity. FR4 material is used as antenna substrate and dielectric strips considering low fabrication cost and ease of availability. The complete insertion or removal of dielectric strips from the three cavities can provide eight different arrangement of the dielectric material inside the antenna system. The reflection characteristics corresponding to eight different cases are shown in Figure 5 and Figure 6. Empty cavity is denoted by '0' and '1' denotes complete insertion of dielectric strip inside a particular cavity. When dielectric strips are inserted in $C1$, $C2$ and $C3$ sequentially, the effective dielectric constant of the antenna system increases. Hence, the resonant frequency shifts towards lower frequencies as shown in Figure 5. Since the cavities are designed symmetrically with respect to the patch and substrate height, the insertion of single dielectric strip in anyone of the cavities results in nearly same variation in effective dielectric constant. As a result, resonant frequencies in case 2 (0-0-1), case 3 (0-1-0) and case 5 (1-0-0) are nearly equal. Similarly, case 4 (0-1-1), case 6 (1-0-1) and case 7 (1-1-0) provides resonance near around 2520 MHz. The resonant frequencies and gain corresponding to eight different cases are depicted in Table 1. It is observed that the proposed mechanical reconfiguration technique can provide eight different resonant frequencies without significant variation in gain. At the same time, the antenna maintains a stable radiation pattern in the tuning

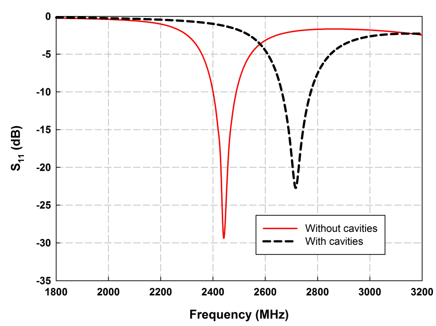

Figure 3. Reflection characteristics of the proposed antenna with and without the inclusion of cavities

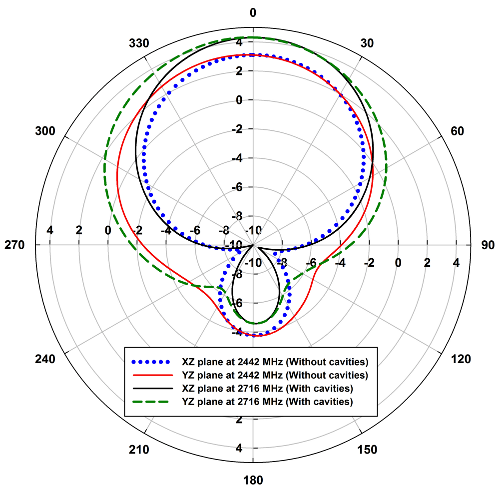

Figure 4. Radiation pattern of the proposed antenna with and without the inclusion of cavities

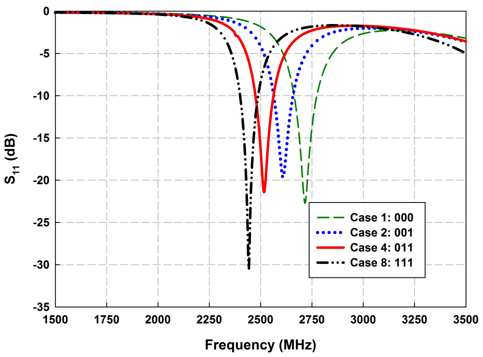

Figure 5. Configuration 1: Variation in the reflection characteristics for cases 1,2,4 and 8

frequency range. The mechanical frequency reconfiguration technique used in this paper is less complex in comparison to the electrical frequency reconfiguration techniques which employs varactor diodes or pin diodes along with the biasing circuits. Thus the ohmic losses arising due to these elements are avoided in mechanical reconfiguration technique. Moreover, by increasing the the number of cavities inside the substrate and the use of dielectric strips of different permittivity tunable frequency range can be broadened.

3.2 Fluid Level Sensor

The antenna proposed in Section 3.1 can be employed as fluid level sensor with slight modification in the geometry as shown in Figure 2. The three cavities are connected to single fluid inlet. The rise/fall in the fluid level modifies the resonant frequency of the proposed antenna. The principle behind the fluid level sensor is the variation in effective dielectric constant of the antenna substrate with the change fluid level. In this paper, diesel (ε_r = 2.1) level sensor has been proposed as a proof of concept. As the inlet opens, the

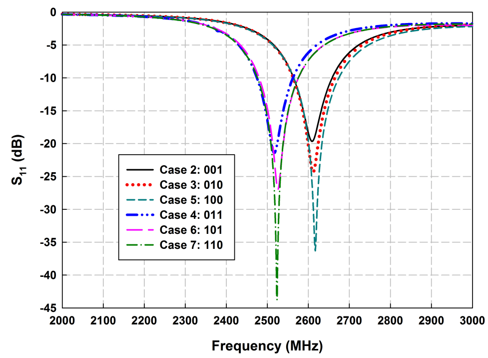

Figure 6. Configuration 1: Variation in the reflection characteristics for cases 2,3,4,5,6 and 7

Table 1. Configuration 1: Frequency and gain variation

Case	C1	C2	C3	Freq. (MHz)	Gain (dBi)
1	0[a]	0	0	2716	4.39
2	0	0	1[b]	2609	3.95
3	0	1	0	2612	3.98
4	0	1	1	2517	3.55
5	1	0	0	2617	4.01
6	1	0	1	2526	3.61
7	1	1	0	2524	3.60
8	1	1	1	2442	3.20

[a] 0 - empty cavity, [b] 1- complete insertion of dielectric strip.

diesel level in the three cavities rises simultaneously which can be detected by the change in resonant frequency of the sensor. The dimension of the fluid channel has a significant effect in the level sensing range as well as the radiation characteristics of the antenna element. The dimension and the alignment of the fluid channels are optimized based on the dielectric constant of the fluid sample and measurable fluid level. The effect of the orientation of the fluid inlet on the radiation characteristics of the proposed antenna is also investigated. Two different inlet positions as shown in Figure 7 is analyzed and found that the shift in resonant frequency is negligible as depicted in Figure 8. Thus the choice of two antenna geometries with different fluid inlet orientation holds less significance. Therefore, in this

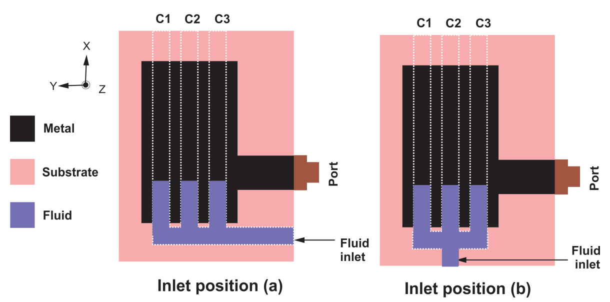

Figure 7. Schematic with different inlet positions

Table 2. Configuration 2: Frequency and gain variation

Fluid level (mm)	Freq. (MHz)	Gain (dBi)
5	2683	4.41
10	2662	4.29
15	2653	4.32
20	2649	4.31
25	2634	4.26
30	2599	4.08

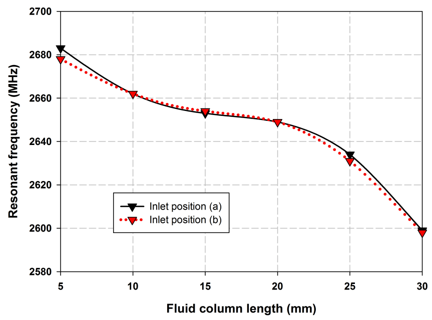

Figure 8. Variation f_r due to change in fluid inlet position

research prototype with inlet position (a) is considered for analysis. The change in the resonant frequency of fluid level sensor with rise in diesel level is illustrated in Table 2. It is observed that an increase in diesel level from 5 mm to 30 mm causes a frequency shift of 84 MHz (2683 MHz- 2599 MHz). The prototype shows a stable radiation pattern in the sensing range (5 mm-30 mm) with a maximum gain of 4.41 dBi and 4.08 dBi at 2683 MHz and 2599 MHz respectively. Hence, a small increment in fluid level can also be detected easily using this sensor. It makes the proposed antenna a potential sensor in remote fluid level monitoring in IoT systems. Since the same antenna operates as a sensor and a transmitter, it reduces complexity and size of wireless sensor networks. Moreover, standard reference data corresponding to different fluid level can be generated for specific fluids for various applications.

4 Conclusion

A mechanical frequency reconfiguration technique for wireless sensor application is discussed in this paper. Frequency reconfiguration is achieved by varying the dielectric properties of antenna system mechanically. A tunable frequency range from 2442 MHz to 2716 MHz is obtained using this technique. In future, the tunable frequency range can be increased by using more number of cavities inside the substrate or by using dielectric strips of different permittivities. In the second configuration, the application of the proposed reconfigurable antenna as a fluid level sensor is analyzed. The fluid used in the present study is diesel. The rise/fall of diesel in the cavities is sensed by the shift in the resonant frequency of the antenna. The proposed fluid level sensor is simple and compact. Since it employs integration of the sensor and the transmitter into the antenna itself, the need for extra components in the sensor system is eradicated. Also, the delays associated with these extra components are removed. This shows that the proposed antenna can act as a fast wireless sensor with reduced power consumption. These features make the prototype a promising component of IoT systems.

5 Acknowledgements

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