A Discussion on Reconfigurable and Frequency Agile Planar Antennas

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Abstract—Reconfigurable and frequency agile antennas are getting popular because they tend to reduce number of antennas to meet several wireless communication applications on a given devices such as mobile phones, tablet PCs, and wireless routers. However, this benefit comes at the cost of some trade-offs such as complexity in antenna design, fabrication and experimental verification including reduced antenna performance than a passive antenna. In this article, some of these aspects are discussed mostly based on the authors published research work. Interested readers are encouraged to read referenced papers for additional details.

Keywords—Reconfigurable antennas, Frequency agile antennas, Printed antennas, Wireless communications.

I. INTRODUCTION

Modern communication systems prefer different forms of the reconfigurable and frequency agile or tunable antennas to accommodate several wireless communication applications in a handheld or portable device [1]. A reconfigurable antenna is used to achieve polarization reconfiguration or radiation pattern reconfiguration or reconfigurable operating frequency or combination of these. These can be achieved by judiciously connecting or disconnecting different parts of the antenna geometry or tailoring the current distribution on the antenna surface/volume by employing RF switching diodes such as PIN diode, RF MEMS switch, or FET based switches. Compared to this, a frequency agile or tunable antenna is the one, where antenna operating frequency is tuned by employing a tunable device such as a varactor diode in an antenna structure or by mechanically changing the antenna substrate thickness [2]. In both cases, by consolidating the number of antennas required, the overall size of the device system is decreased. In this article, some of these aspects are presented based on the published research work performed by the author in collaboration with other researchers at both the University of Manitoba and San Diego State University. Interested readers are encouraged to read referenced papers for additional details.

II. FREQUENCY AGILE ANTENNAS

In this section, difference between the different forms of frequency agile or frequency tunable antennas is presented. Basic technique to design frequency agile antennas is also included. There are different possibilities for realizing a frequency agile antenna such as by employing (i) ground plane reconfiguration, and (ii) varactor diode, RF MEMS diode, or other diode types. Frequency agile antennas operate in the desired narrow frequency range while rejecting neighboring ones thus less stress is placed on RF filtering compared to a commination system employing multiband or wideband antennas.

2.1 Frequency Agile Antennas using Ground Plane Reconfiguration: Ground plane reconfiguration concept has been studied in [3-7] first for the delay kind microstrip transmission line phase shifters [3-4] and then for frequency tuning of narrow band and wideband microstrip patch antennas [5-7]. This technique avoids complex RF biasing network for variable diodes offering variable capacitance and operates on the inherent characteristics of the patch itself. In this case, frequency tunability is achieved by altering the height of the ground plane as shown in Fig. 1(a) [3-4]. However, this technique requires high level of electrostatic actuation to vary the ground plane height. The limitations are repeatability, very limited ground plane height variation and complex fabrication of the reconfigurable ground plane structures such as using micro- and nano-fabrication methods for creating the membrane structure which gets deflected as electrostatic actuation is applied.
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lowest frequency (1.36GHz) which also corresponds to the maximum varactor capacitance of 9.63 pF. Similarly, with 15 V bias, capacitance equivalent values of R, L, C (based on varactor diode data sheet) are modeled as lumped circuit components.

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tuned between 1.36GHz to 1.57GHz which corresponds to 17% frequency variation. With the increase in airgap height (\( h_a \)) to 3.2mm, the frequency shifts to the lower end and operates at 3.4 GHz showing dual band performance with the first band operating in 3.26 to 3.6GHz (9.91% BW). The second band is operating in 3.91 to 4.34GHz (10.42% BW). As the height \( h_a \) is increased to 4.8mm, the frequency shifts more towards the lower end and operates as wideband antenna with 35% bandwidth (3.09 to 4.40GHz). With further increase in height to 6.4mm, the lower end frequency shifts to 3.0GHz with operational bandwidth of 34.71% (3.0 to 4.26GHz). With airgap height of 7.8mm, the USLMES resonates between 3.26 to 3.75GHz offering 13.98% bandwidth. Thus, the effect of employing different heights of ground plane makes this antenna frequency tunable/agile which operates with single, dual and wideband responses. Although not shown here, this antenna possessed directional radiation pattern with good gain between 5 and 10dBi for various airgap heights.

Similarly, Fig. 1(d) shows the implementation of a frequency tunable/agile antenna in a three elements linear array showing beam steering performance by employing variable airgap heights [6]. As can be seen, the three E-shape patch antennas are placed at airgap heights of 210 \( \mu \)m, 412 \( \mu \)m, and 614 \( \mu \)m offering 0°, 90° and 180° far-field phase shifts at operating frequency 94 GHz. Impedance matching performance of this antenna is shown in Fig. 1(e) where it can be observed that the three patches have different matching bandwidth performances. In this case, common bandwidth and common operating frequency is an important parameter, for example at 94GHz, all the patches are matched below \( S_{11} = -10\)dB. The concept of far-field phase shift is shown in Fig. 1(f), where it can be seen that, with the airgap height variation between 200\( \mu \)m to 600\( \mu \)m, a far-field phase shift of 180° can be obtained. Here, the far-field phase shift is phase response of the radiated far-fields which varies as airgap height is changed.

2.2 Frequency Agile Antennas using Variable Capacitors: Frequency agile antennas can be designed by incorporating tunable components in a radiating element in suitable placement arrangements. Tunable components can be of variable capacitor or variable inductor type, however variable capacitors are easily available. Most popular variable capacitors are known as varactors which operate under reverse bias voltage. RF MEMS variable capacitors are another option. These capacitors can be placed between the radiating element and the ground plane or at the same level as the radiating elements. The placement arrangement affects antenna tunability performance. In this article, varactor placement at the level of the radiating element is discussed.

In order to actuate a tunable component, bias networks are implemented using lumped circuit components (R, L, C) and must meet physical and electrical specifications such as component size and low loss throughout the frequency of operation. The same criterion applies to selection of an appropriate tunable component. While performing simulation design, it is also necessary to include parasitic R, L, C values associated with the component packaging as much as possible. Length and diameter of bias wires and battery placements also affect the antenna performance hence must be included as part of the antenna geometry and performance optimization.

Fig. 2(a) shows a frequency agile concentric circular patch antenna where four varactors (Skyworks SMV 1234) are placed between the central patch and the outer ring patch. The location of diode placement is determined based on the maximum of the surface current distribution. Two feed ports are selected so that both linear and circular polarizations can be obtained by suitably exciting feed points. These patches are operating in dominant mode throughout the frequency agility range. At the low frequency, both central patch and the outer rings are working as single patch antenna whereas at the higher end, only central patch is primarily resonating in the dominant mode, TM_{11}. Fig. 2(b) shows equivalent circuit of the varactor diode along with its bias components which use DC blocking capacitors and RF choke inductors. For the presented antenna, values of the DC blocking capacitor and RF choke inductor are 12 pF and 22nH, respectively. Technique for modeling it using Ansys HFSS is shown in Fig. 2(c) where equivalent values of R, L, C (based on varactor diode data sheet) are modeled as lumped circuit components. As varactor capacitance or bias voltage is varied frequency response varies, as shown in Fig. 2(e). With 0V bias, the antenna resonates at the lowest frequency (1.36GHz) which also corresponds to the maximum varactor capacitance of 9.63 pF. Similarly, with 15 V bias, the antenna operates at 1.57GHz which corresponds to the minimum varactor capacitance of 1.32 pF. Thus, this antenna provides frequency agility or tunability between 1.36GHz to 1.57GHz which corresponds to 17% frequency agility. It should also be noted that response of both feed ports are not exactly the same because of the dissimilarities of the two varactors, and other fabrication errors such as the length and diameter of bias wires and battery placements. These fabrication errors also affects the antenna
performance hence must be included as part of the antenna geometry and performance optimization. The series resistance ($R_s$) of the varactor directly affects the total antenna efficiency which is shown in Fig. 2(f). As series resistance ($R_s$) is increased, the antenna efficiency drops due to increase in Ohmic loss inside the varactor. Therefore, it is recommended that, lower $R_s$ value varactor diodes should be selected in an antenna design. Further, effect of this varactor resistance is more detrimental towards the lower end of operating frequency than the highest frequency. The efficiency drop towards the lower frequency is in general depending upon the reduced antenna directivity towards the lower frequency than the highest frequency. This is because the effective aperture area of the fixed physical size antenna gets electrically smaller as frequency decreases or wavelength increases.

Although not shown here, by applying bias voltage to two varactors each along with one feed point, vertical and horizontal linear polarizations is achieved. Similarly, applying the same bias voltage to all the varactors and exciting both feed points in $\pm 90^\circ$ time phase difference, right hand (RH) or left hand (LH) circular polarizations is obtained [8].

These frequency agile antennas can also be placed in array fashion to obtain frequency agile array antennas. For example, the antenna (Fig. 2) in [8] was also implemented as linear array and planar array which showed beam steering performance while achieving simultaneous frequency tunability/agility and polarization reconfiguration [9]. Fig. 3(a) shows top view of a 2x2 planar array antenna. The frequency tunable impedance matching response with varactor diode capacitance variation is shown in Fig. 3(b) which offers 1.16 GHz to 1.58GHz range frequency agility. Since this array antenna is also being simultaneously reconfigured for polarization, its circular polarization and linear polarization radiation patterns are shown in Figs. 3(c-d), respectively. The 2x2 array factor is making beamwidth narrower for both cases than to a single radiating element beamwidth.

Similarly, a dual mode (TM$_{11}$ and TM$_{21}$) circular microstrip patch antenna combined with an annular ring offers frequency agility and polarization reconfiguration in [10]. In here, using varactor diodes, the operating frequency of the both modes can be tuned between 1.58 GHz to 1.19 GHz with $S_{11} = -10$dB. Each of the modes (patch and ring antenna) employ two feed SMA ports with 90° and 45° angular separation for TM$_{11}$ and TM$_{21}$ modes generation, respectively. By suitably exciting these ports, four different polarizations: linear vertical, linear horizontal, left hand circular polarization (LHCP) and right hand circular polarization (RHCP) can be generated simultaneously with the frequency tunability/agility. Such an antenna can be a good candidate for null and limited beam peak steering used in anti-jamming applications. For sake of brevity, additional details are not shown here and the readers are referred to review [10].

![Fig. 3: (a) A 2x2 planar array antenna, (b) Frequency response as varactor capacitance varies, (c) circularly polarized and (d) linear polarized gain radiation patterns [9].](image-url)
Reconfigurable antennas are realized by judiciously connecting or disconnecting different parts of the antenna geometry with the help of RF switches. Frequency reconfiguration, polarization reconfiguration and radiation pattern reconfiguration are the three possibilities. Below, each of these types of reconfigurable antennas is discussed. In order to actuate a RF switch, bias networks are implemented using lumped circuit components (R, L, C) and must meet physical and electrical specifications such as component size and low loss throughout the frequency of operation. The same criterion applies to selection of an appropriate RF switch. While performing simulation design, it is also necessary to include parasitic R, L, C values associated with the component packaging as much as possible. Length and diameter of bias wires and battery placements also affect the antenna performance hence must be included as part of the antenna geometry and performance optimization.

4.1 Frequency Reconfigurable Antennas: A frequency reconfigurable antenna provides the capability for the antenna to operate in only the desired frequency range while rejecting neighboring ones. This reduces interference which will consequently increase signal to noise (S/N) ratio. Compared to this, a multiband antenna covers multiple bands simultaneously hence will require RF filters to separate RF signals as application communication band is varied.

Mechanism for designing a frequency reconfigurable antenna relies on the control of the surface current distribution on the radiating element by turning ON and OFF the specific portions of a radiator [11]. For example, a frequency reconfigurable compact planar dipole antenna is shown in Fig. 5 [12]. This antenna achieves miniaturization by approximately 50% by incorporating spiral shape at ends of the dipole. By incorporating PIN diodes along with the necessary bias networks at the appropriate locations on the antenna, the antennas shows three reconfigurable bands at 2.4GHz (Fig. 5(a)), 1.8GHz (Fig. 5(b)) and 750MHz (Fig. 5(c)). Similarly, simulated 3D gain radiation patterns are shown as (a-c) for the three reconfigurable frequencies 0.750GHz, 1.8GHz and 2.4GHz, respectively. The antenna provides nearly omni-directional radiation patterns.
A frequency reconfigurable spiral loaded planar dipole antenna provides three narrow bands at the specified frequencies by controlling current distributions. Current distributions are shown at (a) 2.4GHz, (b) 1.8GHz, and (c) 0.750GHz. Similarly, 3D gain radiation patterns are shown as (a-c) for the three reconfigurable frequencies 0.750GHz, 1.8GHz and 2.4GHz, respectively [12].

Another antenna example to illustrate the frequency reconfigurable antenna mechanism is shown in Fig. 6(a) which provided three wideband reconfigurable antenna performance by selectively turning ON/OFF PIN diode and consequently, the portion of antenna structure shown as the case 1, case 2 and case 3 [13]. PIN diodes were placed at the appropriate locations on the antenna structure along with the necessary bias networks (Fig. 6(b)). Ansys HFSS model for a PIN diode is shown in Fig. 6(c) which uses lumped components. This can be assigned using boundary conditions. The equivalent circuit for the ON and OFF states of a PIN diode switch is shown in Fig. 6(d). Similarly, equivalent circuit for the bias network is shown in Fig. 6(e) where blocking capacitors and choke inductors are used to isolate RF signal from the DC bias signal. In the forward (ON state) path, blocking capacitor \( C_B \) offers low impedance (or low reactance) hence RF signal will pass through, whereas, the choke inductor \( L_C \) will offer very high impedance (or high reactance) therefore RF signal will be isolated from the DC signal. Frequency reconfiguration response of this antenna is shown in Fig. 6(f) where three wideband (Case 1: 43%, Case 2: 70%, and Case 3: 93%) frequency reconfigurations are obtained. Although not shown here, this antenna offers near omni-directional radiation patterns.

A novel compact multiband frequency reconfigurable quasi-log periodic dipole array (QLPDA) antenna is presented in [15] and shown in Fig. 7(a). It employs eight PIN diode RF switches showing different reconfigurable options based on the different RF switch states, namely, ALL ON, A OFF, AB OFF, ABC OFF and ABCD OFF (Figs. 7(a, c)). The equivalent circuit for the PIN diode and bias network is shown in Fig. 7(b). Followed by this, full wave analysis was performed to design this antenna which included antenna, RF diode equivalent circuit, and bias network. It provided frequency reconfigurable performance across four of five dipole elements operating between 1.8 GHz to 7.0 GHz. Omni-directional to end-fire directional radiation patterns were achieved at the specific frequencies within the band. The antenna was fabricated and experimentally verified for the both impedance matching and radiation patterns. Measured reflection coefficient results for the different switch states are shown in Fig. 7(c) which shows that as RF switches are turned OFF from low frequency (larger dipole), only higher frequency bands are matched. This is important to add that, some leakage current still happens, which should be practically minimized so that unwanted bands are completely turned OFF.
4.2 Radiation Pattern Reconfigurable Antenna: To illustrate the mechanism of operation of a radiation pattern reconfigurable antenna, an example is shown in Fig. 8. A microstrip planar Yagi-Uda antenna with PIN diodes and necessary bias circuits provides end-fire radiation pattern reconfigurability by switching the patterns in opposite directions while still maintaining the pattern shape and impedance matching bandwidth [16]. Side 1 “ON” or Side 2 “ON” refers to the set of PIN diodes in the ON state so that reflector, fed dipole and director elements can be reconfigured so that a specific direction end-fire beam can be realized. As Side 1 is ON, current distribution is localized near reflector, fed dipole and director. Similarly, when current is localized in the reverse direction, Side 2 is ON, thereby end-fire pattern direction changes in opposite direction. Fig. 8 also shows fabricated antenna photograph and measured far-field patterns at 1.45GHz, 1.50GHz and 1.56GHz with radiation patterns in opposite direction demonstrating radiation pattern reconfiguration.

4.3 Polarization Reconfigurable Antenna: Polarization reconfigurable antenna is the one, where either of the polarizations: vertical linear, horizontal linear, right hand circular polarization (RHCP), and left hand circular polarization (LHCP) can be generated in an antenna structure. One such antenna is as shown earlier in Fig. 2(a-b). The frequency tunability is as shown in Fig. 2(e). Now if a polarization reconfiguration circuit can be implemented with this antenna having two feed ports, either of the polarizations can be excited. A simple version for this is to use a quadrature branch line power divider where equal power division with 90° phase difference can be obtained which will offer CP pattern. This is shown in Fig. 9(a) along with the antenna but with 6 inches long coaxial cables. Now, if we want to generate only vertical or horizontal linear polarizations, we can simply excite either of the ports in the antenna while the other port is matched terminated. In this case, quadrature power divider is not needed. However, when RHCP or LHCP patterns are required, either port 1 or port 2 of the coupler can be excited while the remaining port is matched terminated. Thus, all four polarizations can be generated. Comparison of the simulated and measured axial ratio (AR) for the RHCP and LHCP cases are shown in Fig. 9(b-c), respectively. It should be noted that, while this polarization reconfiguration happening with this antenna, it is capable of simultaneous frequency tunability as discussed earlier.
In this article, difference between the frequency agile/tunable antennas and reconfigurable antennas are presented in addition to their basic types and some antenna examples from the author’s published/unpublished work. It should be noted that, extensive research work on these topics is under way at several universities and research groups throughout the world including the author’s research group. Since this article only focused on the author’s work, it does not claim it is complete in any sense. Interested readers are requested to read published literature including the ones given in this paper’s references to gain additional insight to the references. One of the limitations of the reconfigurable and frequency agile/tunable antennas is the unavailability of RF components towards the higher frequency range with reduced loss resistances. Therefore, most of the reported antenna works are focused towards lower GHz frequency range. Additionally, physical signature of the radiating elements reduces as frequency increases and therefore, if the RF components physical signature would stay the same as current RF components, it would hinder the design and development of efficient reconfigurable and tunable antennas towards higher frequency spectrum. Further, even if smaller size RF components are made available, precise placement and soldering of these on the antenna structure is very challenging and cannot be accomplished at least using the conventional surface mount component soldering stations. Another limitation is the fractional frequency bandwidth over which frequency agile/tunable and reconfigurable antennas can be designed with acceptable radiation performance. Type of the radiating elements that can be employed as part of the frequency agile and reconfigurable antennas is also limited to mostly planar or printed antennas including some configurations of dielectric resonator antennas.

Employing frequency agile and reconfigurable antennas as part of the array antenna implementations for high gain performance, multiple input multiple output (MIMO) antennas and on flexible substrates such as PET films are current and future research study directions. Reconfigurable and frequency tunable antennas as MIMO antennas are the current research directions of the author’s research group, in addition to their array implementations [9, 11, 17, 18]. Application of metasurfaces to improve performance of the reconfigurable and frequency tunable antennas is also a challenging task which needs attention.

ACKNOWLEDGEMENTS

National Science Foundation (NSF)’s CAREER Grant # ECCS-0845822 and the graduate students of the AML, SDSU, who are involved in the reconfigurable and tunable antennas research activity.

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