A Review of Achieving Frequency Reconfiguration for Antennas in Wireless Communications

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Abstract—Reconfigurable antennas are a type of smart antenna that is able to change whose properties, including resonant frequency, polarization, radiation pattern, and a combination of these properties. Reconfigurable antennas can switch between their configuration states to operate at different frequency bands for multiple standards, change their radiation patterns for direction finding, or change their polarization for polarization diversity. Therefore, they are a solution for modern wireless communications to meet the requirements of the system's multi-functionality. This paper presents different reconfigurable antennas with various techniques to obtain antenna reconfiguration. The reconfigurable antenna can be achieved using electrical components (PIN diodes, RFMEMSs, varactors, FETs), optical diodes, smart materials (liquid crystal or ferrites), or physical alteration of antenna structures. The comparison and summarization of different reconfiguration techniques are described in the paper. The publications on reconfigurable antennas are mentioned and illustrated with discussions.

Index Terms—reconfigurable antenna, cognitive radio, PIN diodes, frequency reconfigurable antenna.

1. Introduction

In order to operate on multiple standards for different applications, handsets have been integrated with a number of single-band antennas, multi-band antennas, or wideband antennas. However, the disadvantage of using multiple single-band antennas is that the antenna space increases, leading to an increase in the device size and an increase in the cost of the equipment. With multiband or wideband antennas, only one antenna can meet many different operating frequencies, saving cost and equipment size, but the disadvantage of this type of antenna is interference between neighboring bands. close. To solve the problem of interference between neighboring bands, the filter requirements for the system become more complicated [1]. The concept of reconfigurable antennas with the ability to automatically change the radiated frequency, radiation graph, polarization, or combination of parameters in the world to solve the problems of the above problem [2]. For a frequency reconfigurable antenna, it can switch in different configurations to operate at many different frequencies in order to increase frequency utilization efficiency and adapte to changes in environmental channels. Furthermore, the frequency reconfiguration antenna can replace a multiband antenna or a number of singleband antennas resulting in space savings for handsets and less complexity for system filtering [3-9]. Reconfiguration can be implemented by integrating electronic components, optical switches, capacitors, and smart materials, as well as changing physical structures to change the surface current distribution or electromagnetic field of the antenna, resulting in a change in the impedance or radiation characteristics. Among them, integrating the power switches as PIN diodes or RF-MEMS into the antenna is the most popular method today. For use of PIN diodes or RF-MEMS, the designer can change the radiated element length, impedance matching, or antenna structure to reconfigure antennas. Moreover, increasing channel capacity and data rate is also a requirement of the radio communication system. Therefore, MIMO (multiple input multiple output antennas are widely used in wireless communication systems [10-11]. To combine the advantages of MIMO antennas and reconfiguration antennas, MIMO reconfiguration antennas are a potential solution for enhancing flexibility, providing multiple functions, reducing the cost and size of handsets, as well as increasing the channel capacity and data rate of the systems. The rest of the paper will discuss the different configuration techniques, the advantages and disadvantages of each technique, and applications of reconfigurable antenna configuration.

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2. Reconfiguration techniques

2.1. Classification of reconfigurable techniques

There are various techniques for antenna reconfiguration. Based on changing the antenna structure, they are classified into four categories as shown in Fig. 1. The antennas are integrated with electrical components to change the surface current distribution, such as radio microelectromechanical system (RF-MEM) switches [1-17], PIN diodes [18-24], field effect transistors (FETs), and variable diodes [25-29]. The reconfiguration technique that uses electronic switching elements is currently popular because it has a lot of advantages, as presented in Section 2.2. In addition, the antenna is reconfigured using optical switching [30-33], physical alteration to antenna structures [34-36], or materials such as ferrite or liquid crystals [37-39]. These techniques are described in detail in sections 2.3-2.5.

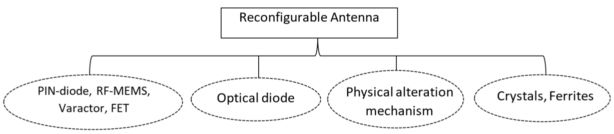

Fig. 1: Antenna reconfiguration techniques [12]

2.2. Reconfiguration technique based on electrical components

Most reconfigurable antennas use electrical switches to change the structure of the antenna's radiated surface or radiated edge, resulting in changes to the surface current distribution [40]. Electrical switches include PIN diodes, RF-MEMS, FETs, and variable diodes. This technique has attracted antenna designers because electrical components are compact and it is easy to integrate them into antennas.

2.2.1. Reconfiguration based on PIN diodes

The PIN diode is a semiconductor component that can operate in the ultra-high frequency range. It is very popular for radio circuit applications because of its high switching speed [4]. The structure and symbol of a PIN diode are shown in Fig. 2.

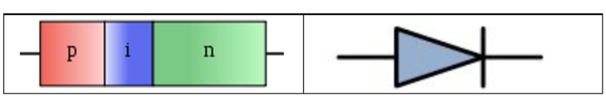

Fig. 2: Structure, symbol of a PIN diode

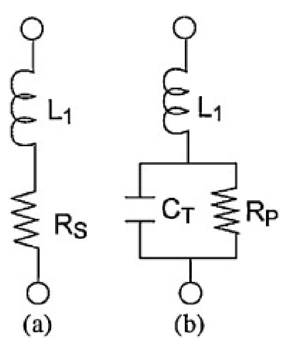

Fig. 3: Equivalent model of a PIN diode: a) ON, b) OFF

Fig. 3 shows the equivalent circuit diagram of the PIN diode. A PIN diode has two states, ON and OFF, which are switched by a bias voltage. When forward voltage is applied to the diode's anode and cathode terminals, the diode is in the ON state (closed), which is the same as a resistor R_S connected in series with an inductor L_1. In contrast, when the reverse voltage is applied to the diode, it is in the ON state, which is equivalent to a circuit consisting of a resistor RP connected in parallel with a capacitor C_T and in series with L_1. The diode is closer to the ideal as the values of C_T and R_S are reduced and the value of R_P is increased. In fact, these values depend on the operating frequency range and the specific properties of each PIN diode made by different manufacturers.

The PIN diode's benefits are that it only needs a small bias voltage (3–5 V), has low loss, good isolation, and is low cost. It also has a fast switching speed $(1\text{–}100ns)$, which is the fastest compared to all other types of switches [40]. Therefore, PIN diodes are currently widely used in wireless communication. However, the drawback of the PIN diode is the requirement for integrating elements such as capacitors and resistors into the bias circuit of the PIN diode, making the antenna more complicated and increasing the antenna's power consumption [41-43]. When the diode is built into the antenna, using DC power lines to control it will affect the radiation efficiency. This is a disadvantage of all types of electrical switches. To reduce the effect of biasing lines on the antenna radiation pattern, antenna designers need to make as few of them as possible and design the simplest and most optimal power supply circuit. Moreover, the power consumption of the PIN diodes is quite high, ranging from 5 to $100mW$ [40]. Therefore, when integrating the PIN diode into the antenna, it is necessary to choose a diode with low power consumption to reduce the total power consumption of the antenna. A proposed reconfiguration antenna using the PIN diodes in [44] is shown in Fig. 4. The antenna uses three diode PINs to achieve four different frequency reconfigurations by changing both the length of the radiated element and the feeding network.

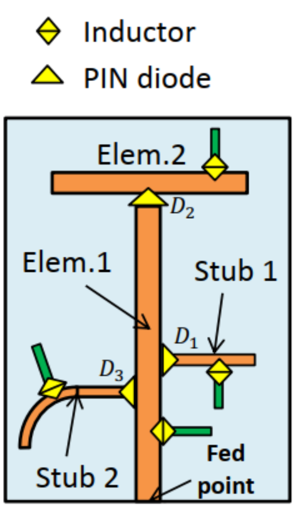

Fig. 4: Structure of a reconfigurable antenna based on PIN diodes [44]

2.2.2. Reconfiguration based on RF-MEMS

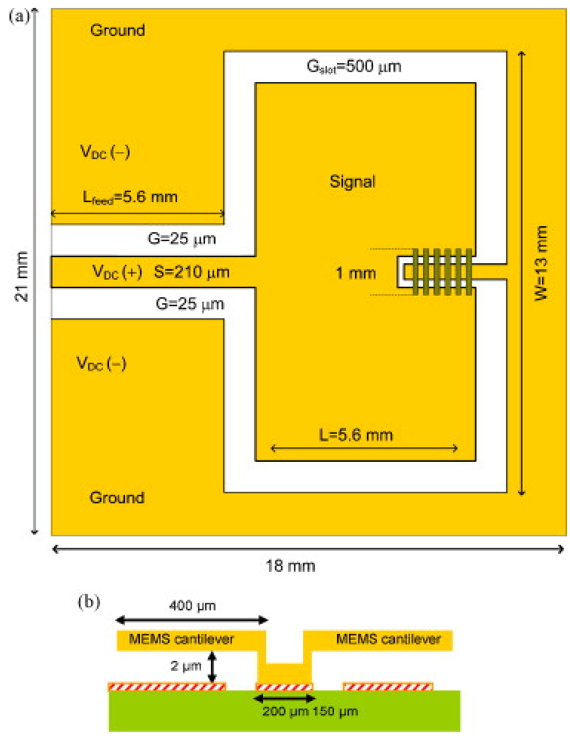

Fig. 5: Structure of reconfigurable antenna based on RF-MEMS [45]

RF-MEMS is an electronic system integrated with a micrometer-sized mechanical movement structure. It is the integration of mechanical elements, sensors, triggers, and electronic elements on a silicon patch by microfabrication technology. RF-MEMS is a special mechatronic switch used to short or open a circuit for transmission lines at high frequency. The advantages of RF-MEMS switching are low power consumption, low loss, and good isolation. However, the drawback of using MEMS for reconfigurable antennas is the requirement of a high DC voltage source (from 20 to 100 V). Besides, the switching speed of MEMS is much slower than that of a PIN diode. For applications requiring high switching speeds, RF-MEMS is not the best choice. Despite these disadvantages, RF-MEMS is still widely used in applications in antenna reconfiguration [45-50]. The antenna shown in Fig. 5 [45] is a frequency-reconfigurable slot antenna. Reconfiguration is achieved by using RF-MEMSs and a variable diode. The reconfigured antenna was implemented with two different types of RF-MEMS, including one with a cantilever capacitor and another with a fixed-path capacitor. For the first type of RF-MEMS, when changing the control voltage from 0 V to 32 V, the resonant frequency changes in the range from nearly 9.5 GHz to 12 GHz. For the second type, when changing the control voltage from 0 V to 17 V, the resonant frequency changes in the range from 7.7 GHz to 11.2 GHz.

2.2.3. Reconfiguration based on FETs

A field effect transistor is an electronic switch that can be used in reconfigurable antennas. Fig. 6 depicts the frequency reconfiguration antenna based on FET switch [51]. The reconfigurability is achieved by changing the dimensions of the radiation elements via a FET switch. The antenna can be switched between a narrow-band state and a dual-band state for WLAN, WiMAX, PCS (Personal Communications Service), and WiMAX applications. FETs have the advantages of fast switching speeds similar to PIN diodes and low power consumption. However, the disadvantages of FETs are their low isolation and large losses, so they are not often used for antenna reconfiguration [52].

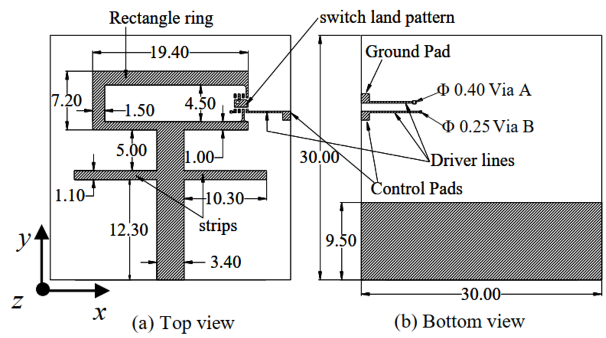

Fig. 6: Structure of a reconfigurable antenna based on FET switch [51]

2.2.4. Reconfiguration based on variable diodes

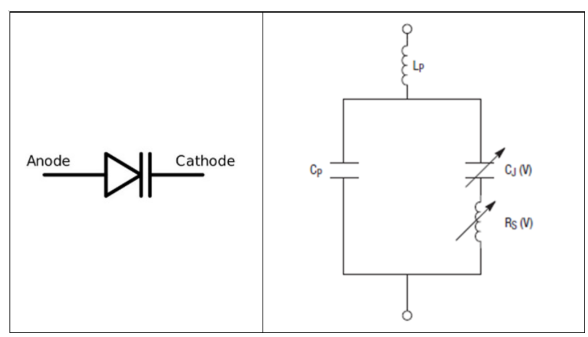

Fig. 7: Symbol, equivalent circuit of a variable diode

The variable diode consists of a contact PN. When the voltage applied to the diode changes, its capacitance will change. The variable diode has a large power consumption and a high control DC voltage. Also, the variable diode is controlled by changing the voltage applied to it, resulting in a complicated bias circuit that has a big effect on antenna radiation. Fig. 7 shows the symbol and equivalent circuit diagram of the variable diode. In the equivalent circuit diagram, $C_J(V)$ is the variable contact capacitance, and R_s (V) is the variable resistance of the PN contact. C_P and L_P are the parameters of the fixed parasitic capacitance and parasitic reactance, respectively, when the variable diode is integrated into the antenna. Despite its disadvantages, the variable diode has the advantages of a small size and a low switching speed (<100 μs), which is considered to be quite good although still slower than the PIN diode. The variable diode is often used in reconfigurable antennas to achieve the continuous resonance frequency [53-55]. A reconfigurable PIFA antenna based on varactor diode is presented in [54]. A varactor diode is integrated between the external semiring and the internal semicircle, as shown in Fig. 8. The operation frequency is continuously changed according to the capacitance value changing from 19 to 1.5 pF, which requires adjustable supply voltages in the range of 0 to 23V.

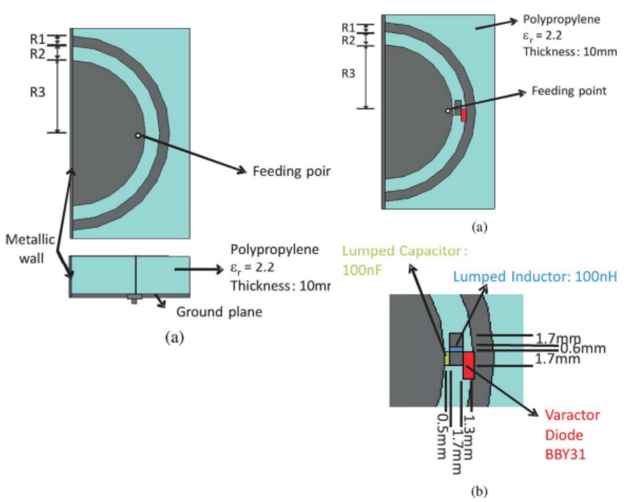

Fig. 8: Reconfigurable PIFA using variable diode. (a)the antenna structure. (b) Zoom of lumped elements and varactor [54]

2.3. Reconfiguration based on optical switches

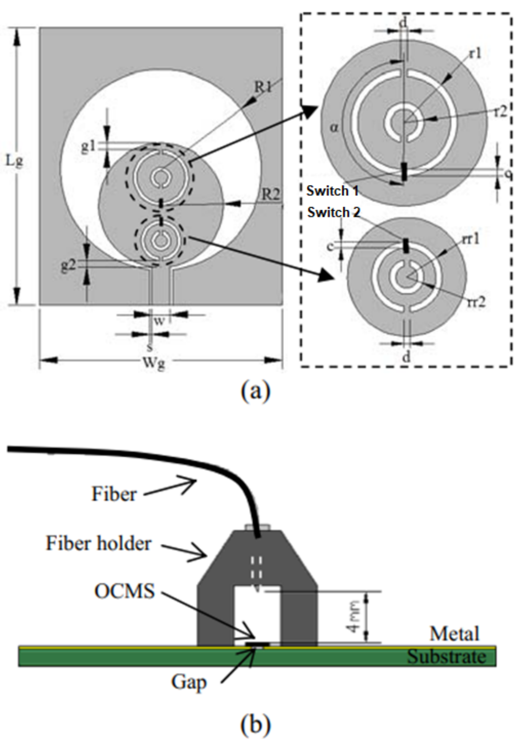

Fig. 9: Optical controlled reconfigurable band-notched UWB antenna: (a) the geometry; (b) the feeding fiber installation [33]

Optical switches are also a solution for antenna reconfiguration. An optical switch conducts when its semiconductor material is lit, which causes electrons to move from the valence band to the conduction band and create the conduction band. There have been several publications on reconfigurable antennas using optical switching [30], [32-33], [56]. Fig. 9 shows the structure of an optically controlled reconfigurable antenna. By changing the states of two optical switches, the antenna archives four different frequency configurations in the FCC-allowed band, the WiMax-notched band, and the WLAN-notched band. The optical switch has linear characteristics and an absence of a bias circuit when integrated into the antenna, so there is no distortion effect on the antenna radiation pattern and no lossy aspect or interference on the antenna. However, the optical switch requires a complex activation mechanism and is expensive, so it has attracted the attention of antenna designers.

2.4. Reconfiguration based on physical alteration mechanisms

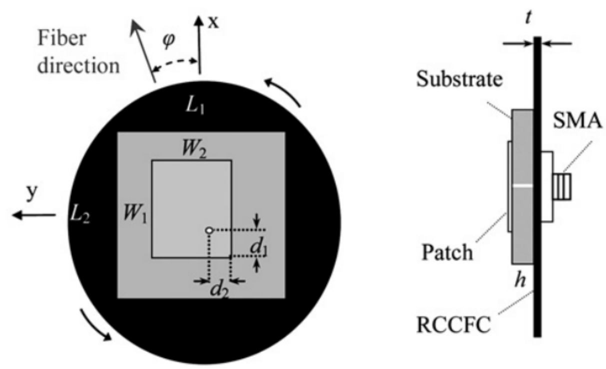

Fig. 10: Reconfigurable rectangular patch antenna based on RCCFC [36]

Antennas can be reconfigured by altering the physical structure of the radiation elements to change the antenna's radiation characteristics [34-36]. By changing the electromagnetic fields that are applied to antennas, the physical structure can be changed to achieve antenna reconfiguration. The rectangular patch antenna grounded by the physical alteration mechanism shown in Fig. 10 was proposed in [36]. The rotation mechanism is based on anisotropic reinforced continuous carbon fiber composite (RCCFC) material integrated in the antenna ground. By rotating the ground plane,the antenna can obtain different operation frequency modes. The advantages of this technique are that there are no requirements for switching mechanisms, bias circuits, or optical fibers. On the other hand, this technique is not widely used due to its limitations, such as its slow response, high cost, and complex physical alteration mechanism.

2.5. Reconfiguration based on smart materials

The reconfigurable antenna can be achieved by using smart substrates such as liquid crystals and ferrites that can change their characteristics in permittivity or magnetic permeability. For example, the dielectric constant of the liquid crystal can be changed by adjusting the voltage applied to the material to control the direction of molecules in the liquid crystal. For ferrites, their characteristics are changed by using electric or magnetic fields. There has been several works in smart material based reconfigurable antennas [37-39]. The proposed antenna in [39] as shown in Fig. 11 is integrated ferrite slabs with applying external magnetic to obtain frequency reconfiguration. In general, the antenna reconfiguration by changing the material has compacted, but its disadvantage is low efficiency.

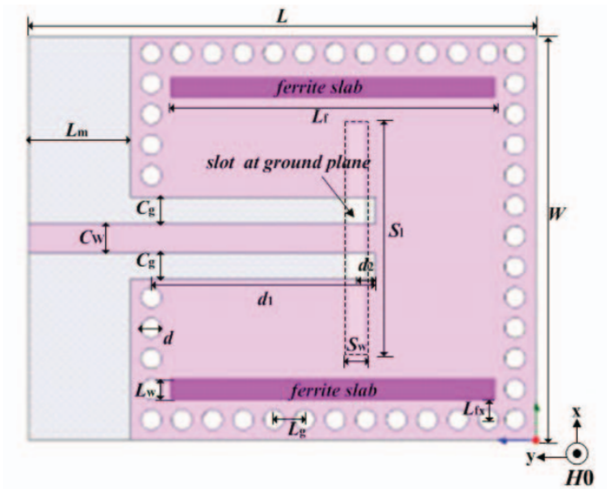

Fig. 11: Structure of ferrite integrated frequency reconfigurable antenna [39]

3. Comparison between different reconfiguration techniques

Each reconfiguration technique has its own advantages and disadvantages. The effectiveness of techniques depends on their particular applications and the requirements of users. However, antenna reconfiguration using electrical switches is the most popular because it has many combined advantages. As mentioned above, the PIN diode has the advantages of low DC voltage, low loss, good isolation, low cost, and fast switching speed. Table 1 summarizes the parameters of common switching elements used in antenna reconfiguration techniques [12].

TABLE 1: Summarization and comparison of the switches' parameters used in reconfigurable antennas

Electrical parameters	**PIN diode**	**RF MEMS**	**Optical switch**
Switching speed	1-200 μs	1-100 ns	3-9 μs
Voltage (V)	20-100	3-5	1.8-1.9
Power consumption(mW)	0.05-0.1	5-100	0-50
Isolation	Very high	High	High
Loss (1-10 GHz) (dB)	0.05-0.2	High	High

4. Conclusion

The main feature of the reconfigurable antenna is the ability to change its characteristics including resonant frequency, radiation pattern, and polarization. Based on that, reconfigurable antennas can be classified as frequency reconfigurable antennas, radiation pattern reconfigurable antennas, polarization reconfigurable antennas, or combined reconfigurable antennas. Several publications on reconfigurable antennas are also analyzed in the paper. With the advantages of high flexibility, increased anti-interference ability, helping to save spectrum, and reducing the number of antennas in equipment, the reconfigurable antenna is a potential solution for cognitive radio communication. However, the challenge is the integration of reconfigurable antennas into the radio system as well as the design of the reconfigurable antenna with a compact structure, a simple switching mechanism, and a minimum number of RF switches and passive components.

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