Batteryless and Self-Reconfigurable Multimode RF Network using All-Passive Energy Smart-Sensing

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ABSTRACT In recent years, replacing the external control stimuli with internal control using characteristics of radio frequency (RF) signals (such as waveform or power level) has attracted considerable attention to the design of reconfigurable multifunctional RF devices. However, even with the most exciting techniques, the control process always needs a chip-based system to sense the power level or waveform of the incident RF signal, which is realised by additional supporting electronic components of the sensing and microcontroller circuits. Therefore, to achieve a batteryless structure, a majority of conventional works focus on using energy harvesters to convert energy from external environmental sources to DC energy for the electronic circuits. Herein, we propose a novel alternative approach to replace the traditional energy harvesters in batteryless RF devices with all-passive energy smart-sensing circuits. By exploiting the features of a nonlinear semiconductor device under different incident RF power values, the proposed network can passively self-sense the RF power level and dynamically self-control RF signal flow and power ratio. The operation of the proposed network can be considered as purely self-adaptation with control from the RF power level. Moreover, normal RF devices can be transformed to all-passive and batteryless purely self-reconfigurable devices via integration with the proposed structure. As proof of concept, the proposed network is integrated with a two-port antenna to experimentally demonstrate its purely self-reconfigurable polarisation. The proposed strategy is hereby expected to extend the field of batteryless self-reconfigurable multifunctional RF devices and pave promising new paths for the development of future intelligent, smart RF devices.

INDEX TERMS Self-reconfigurable, self-adaption, batteryless, multifunctional, all-passive, energy smart-sensing.

I. INTRODUCTION

Since the invention of the first practical radio frequency (RF) system by Guglielmo Marconi [1], [2] in the 1890s, the field of wireless communication has experienced significant diversity with more than a century of intense study and rapid development. From the beginning, controlling radio frequency (RF) signal flow and ratio has always been an important role for the design of both RF devices and systems. For instance, the RF signal flows in the transmitting (TX) and receiving (RX) directions must be separated when the RF transmitter and receiver share a single antenna [3]–[5].

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Moreover, channelisation for frequency division is mandatory in systems that use multiple modulation methods and carriers with single radiated component because of the simultaneous existence of several frequencies [6]. Furthermore, the RF signal flow directly affects the behaviours of modern RF systems such as the multiple input multiple output (MIMO) system [7], [8], and RF devices such as multi-feed antennas [9], [10], phase shifters [11], [12], metasurfaces [13]–[16], and so on. In contrast, excess RF power in one part of an RF system can permanently damage or interfere with the other parts [17], [18]. From the broader system-level view, a typical wireless system contains multiple wireless base stations (BSs) that use similar frequencies [19], [20]; the output RF power ratio between these BSs must therefore be
considered to achieve reasonable carrier-to-noise ratios. The power ratios between different branches of signal flows are also crucial to the behaviour of an RF device, such as the polarisation of a dual-feed antenna [21]–[23], or the beam direction of an antenna array [24]–[27]. Based on these observations, it is obvious that controlling the RF signal flow and power ratio is important and indispensable to determine the behaviour of an RF device.

Conventionally, the strategies for tailoring RF signal flows and ratios can be divided into two groups: static and dynamic manipulations. Static manipulation refers to techniques whose processes are fixed and cannot be reconfigured [28]–[31]. In contrast, dynamic manipulation refers to techniques whose processes can be reconfigured and controlled. Owing to their flexibility and adaptability, dynamic manipulation methods are more suitable for modern intelligent wireless systems. RF signal flows can be dynamically controlled using switch components, such as the single-pole double-throw (SPDT) switch, single-pole multiple-throw switch, double-pole double-throw (DPDT) switch [32]–[35], positive-intrinsic-negative (PIN) diode [36]–[40], transistor [41]–[43], or RF microelectromechanical system (MEMS) [44], [45]. On the other hand, the RF power ratio can be conventionally handled with a variable gain amplifier and an attenuator. Generally, both RF signal flow and power ratio manipulations require external control stimuli along with additional supporting electronic components, such as a microcontroller circuit and DC power supply.

In the era of modern, intelligent wireless systems, the demand for self-operating or self-adapting devices has rapidly increased. To enable a typical reconfigurable RF device/system to be self-reconfigurable or self-adaptable, replacing the external control stimuli with internal control based on the characteristics of RF signals (waveform, frequency, and power level) [46]–[49] and eliminating RF device dependence on the power supply are two indispensable duties. However, most reported works have needed sensing devices to detect the internal characteristics of RF signals and microcontrollers to subsequently configure the state of the RF device/system. Batteryless electronic devices are typically achieved using energy harvesters [50] to convert the energy from an external environmental source (such as mechanical [51], piezoelectric [52], [53], and RF energy harvesting [54], [55]) into DC energy for the electronic circuits. In general, the traditional solutions for self-operating RF devices still require additional supporting electronic subcircuits and subsystems. Although self-operation can be achieved, the complexities of the devices and systems are significantly increased. Moreover, with the rapid development of wireless communication systems, requirements for higher data rates and lower latency connections have risen steeply, which have driven the development of millimetre-wave communication techniques [56]. When the operational frequency of a system is increased, creating control lines or sub-circuits becomes more challenging and places greater pressure on the main control system.

Accordingly, herein, we propose a novel batteryless multimode self-reconfigurable RF network to dynamically control the RF signal flow and ratio after RF power modulation. Further, a novel alternative approach of all-passive energy smart-sensing is presented to replace the traditional method and enable automatic self-switching batteryless operation between the multi-states of RF devices without the support of other electronic devices or DC power supply. The proposed strategy is primarily based on exploiting the characteristics of nonlinear semiconductor devices under different incident RF power values to passively self-sense the power level and integrate it with a static navigator to control the signal flow. We believe that the proposed strategy paves an extendable path for self-operating RF devices and systems as well as enables steady development of future smart RF devices and systems. Moreover, the proposed strategy can be extended to applications in the millimetre-wave frequency range, in which creating sub-circuits or subsystems have been challenging owing to the extremely short wavelengths. First, the operational mechanism of the proposed network is outlined, and the theoretical considerations are explained. Subsequently, we present the strategy to achieve a batteryless multimode self-reconfigurable RF network that can be dynamically controlled by RF power modulation without additional supporting electronic components. As proof of concept, using the proposed network, a purely self-polarisation-reconfigurable (PSPR) antenna, which can be configured by power modulation without any supporting electronic devices, is designed. The concept of “purely self-reconfigurable” is introduced to present devices whose reconfiguration mechanisms are controlled automatically and independently without external control signals, bias circuits, sensing circuits, or DC power supplies. Finally, the potential directions for application of the proposed work are discussed.

II. PRINCIPLE AND DESIGN
A. PROPOSED CONCEPT AND OPERATIONAL ILLUSTRATION

Fig. 1 illustrates the operational mechanism of the proposed network. The power dependence is achieved with the intrinsic characteristics of the proposed device instead of using sensing circuits or energy harvesters for the subsystem supply. Thus, the proposed network can passively self-sense the RF power level and dynamically self-control the RF signal flow and power ratio without using any detectors, sensors, microcontrollers, or power supplies; this novel feature makes the proposed design unique compared with other existing designs. The term “all-passive energy smart-sensing” is used to emphasize the novel features of the proposed network.

The RF signal tailoring processes of the proposed network can be considered as purely self-adaptive, in which each port is visualized as a water pipe with two separate
FIGURE 1. Operation mechanism of the proposed network. RF signal tailoring process is automatically controlled by RF power modulation without supporting electronic components or power supplies. The process can be considered as a purely self-adaption. (a) Different route configurations for channels A and B for each mode. (b) Illustration of port operation, where each channel has power-dependent inputs and can be described as switches that can block (when the switch is OFF) or allow (when the switch is ON) inputs to the channels. (c) Behaviours of ports with different input power values.

halves presented as channels A and B. Fig. 1(c) depicts the behaviours of port 1 and port 2 under different power levels. Specifically, when a low-power RF signal flows into port 1, channel A is blocked, whereas channel B is opened. Hence, the incident wave only follows the route of channel B.

In contrast, the high-power incident wave only follows the route of channel A. Furthermore, the medium-power incident wave places both switches in incomplete ON and OFF states, thereby allowing the incident wave to flow into both channels. When the low-power RF signal flows into port 2, both channels are blocked, which completely reflects the incident wave. When the power of the incident wave is increased, the switch of channel A starts opening whereas that of channel B remains in its OFF state. Hence, the medium-power incident wave is partly reflected and partly flows into channel A. The amount of the wave flowing into channel A increases with increment of the incident wave power until the switch for channel A is completely opened. Port 3 does not depend on the power levels of the incident signals; thus, the two switches are opened with any power level.

B. BATTERYLESS SELF-RECONFIGURABLE MULTIMODE RF NETWORK

Conventional RF devices and systems use diodes as controllable switches, with the two main states ON and OFF controlled by the bias voltages. However, a diode can also self-vary without using bias voltage, such as the power limiter in an RF receiver system. Although the input power does not place the diode in a complete ON state, the incident power level still affects the diode’s equivalent values of series resistance $R_s$, series inductance $L_s$, and parallel capacitance $C_p$, which are demonstrated in Fig. 2(a). Hence, it is possible to design a purely passive two-port network that achieves impedance matching at a specific power level and mismatch at other power levels. The signal at the appropriate power level can be completely delivered through the network, whereas the signal at other power levels are partly or completely reflected. By placing the network under match/mismatch states, we can control both the RF signal flow and output power only by manipulating the input.
TABLE 1. Schottky diode SMS7630 equivalent circuit values.

| Input power (dBm) | $R_s$ (nH) | $C_p$ (pF) | $R_P$ (Ω) |
|-------------------|------------|------------|-----------|
| -20               | 1.5        | 0.22       | 5000      |
| -10               | 1.4        | 0.215      | 4700      |
| 0                 | 1.3        | 0.2        | 4500      |
| 10                | 1.2        | 0.19       | 2400      |
| 15                | 0.8        | 0.18       | 800       |

power levels. To the best of our knowledge, in high-frequency circuits and systems, there are no reported designs that exploit this feature to manipulate RF signal flow and power ratio. The power sensing mechanism can be considered as an all-passive smart-sensing scheme because there are no detectors, sensing circuits, or energy harvesters which have been used.

As a proof of principle, we initially designed and investigated an RF network using a Schottky diode SMS7630 (forward voltage $V_f = 135–240$ mV at 1 mA) to demonstrate mentioned power-dependent characteristics. Firstly, by conducting measurements and parametric studies with full-wave analysis, the diode’s equivalent values of $R_s$, $L_s$, and $C_p$ at different power levels were determined, as given in Table 1. A power-dependent network was then designed and fabricated with a 1.2 mm thick FR4 substrate with dielectric constant $\varepsilon = 4.1$ and loss tangent $\delta = 0.02$. The performance of the designed power-dependent network is measured with a Keysight N5227B PNA; input power levels from $-20$ to 15 dBm were investigated. As can be observed in Fig. 2(b) and (c), the changes on input power level are able to drive the designed network from impedance matching to mismatch state. Specifically, the measured input impedances at 4 GHz varies from $11.05–18.78j$ to $35.44–20.43j$ Ω with input power varies from -20 to 15 dBm. The geometry dimensions of this purely passive power-dependent network are given in Fig. 2(d).

Based on the aforementioned mechanism, the RF signals at different power levels are classified and routed in different directions, although the waves still traverse the same main route. To exploit these differences in signal flows, we propose a batteryless self-reconfigurable multimode (BSRM) network to dynamically control RF signal flow and ratio without additional supporting components (such as controller, sensing, DC power supply circuits), as depicted in Fig. 3. The proposed network is self-reconfigurable via control of incident RF power level. The equivalent circuit of proposed network is presented in Fig. 3(a), and the operational demonstration is depicted in Fig. 3(b)–(d). The circuit structure has the combined form of a power-dependent network and a static navigator. In our design, this structure was realised using a circulator operated along with a diode network at pin C-2 of the internal circulator. The proposed structure uses a Schottky SMS7630 diode, represented by the combination of $L_s$, $R_s$, and $C_p$ in the equivalent circuit. Meanwhile, $C_{TL}$ and $L_{TL}$ represent the inductance and capacitance of the transmission line that connects the internal circulator with the diode network. By configuring a power-dependent network at pin C-2 of the internal circulator, the signal that flows from the outside into port 2 or from the internal circulator to the diode network can be manipulated in other directions only by controlling the RF power level.

The proposed network operates under three different modes, and the mode number represents the port number into which the signal flows. Each mode is further divided into three sub-states for high, medium, and low-power signals. For instance, state I-H represents the case where the incident high-power signal is delivered to port 1, whereas the low-power signal flowing into port 1 is represented by state I-L. The state of the proposed network can be manipulated
only by modulating the power level of the incident signal (Fig. 3(b)–(d)). In state I-H, the signal flows into port 1 and flows out at port 2. When the power level of the input signal is decreased to the low-power threshold, the proposed structure passively changes to state I-L. In this state, the signal flows into port 1 and flows out at port 3. Furthermore, with the medium input power level, designated as state I-M, one part of the RF signal flows out at port 2 and the remaining part flows out at port 3. In general, the proposed network at mode I functions as a controllable power divider manipulated by the RF power level. In state II-H, the high-power signal is delivered from port 2 to port 3. Passively manipulating the operational state to II-L by decreasing the signal level to low power allows the incident signal to be entirely reflected. With medium input power, designated as state II-M, the signal will be partly reflected and partly delivered to port 3. Generally, the proposed network at mode II functions as a filter that only allows signals with the appropriate power levels. Mode III does not depend on the power level, and the signal is delivered from port 3 to port 1 with any input power level.

The relationship of power at the three ports are considered to further explain the control mechanism of the proposed network based on the power ratio. Assume that $T_{21}$, $T_{31}$, and $T_{32}$ are the transmission coefficients of the signal from port 1 to port 2, port 1 to port 3, and port 2 to port 3, respectively; $\Gamma_2$ is the reflection coefficient of the signal flowing into port 2; $P_{\text{low}}$ and $P_{\text{high}}$ are the sequentially low and high power thresholds of the designed BSRM network. Owing to the existence of the power-dependent network at output C-2 of the internal circulator, $T_{21}$, $T_{31}$, $T_{32}$, and $\Gamma_2$ are functions of the input power $f(P_{\text{in}})$. Therefore, the relationship between the input and output signals in each state can be ideally expressed as a function of the input power using the following equations:

- **Mode I:**

$$P_1 = P_{\text{in}};$$

$$P_{\text{out},2} = P_{\text{in}} - |T_{21}| = \begin{cases} -\infty & \text{if } P_{\text{in}} \in (\infty, P_{\text{low}}) \\ P_1 - |T_{21}| & \text{if } P_{\text{in}} \in (P_{\text{low}}, P_{\text{high}}) \\ P_1 & \text{if } P_{\text{in}} \in (P_{\text{high}}, \infty) \end{cases}$$

$$P_{\text{out},3} = P_{\text{in}} - |T_{31}| = \begin{cases} P_1 & \text{if } P_{\text{in}} \in (P_{\text{low}}, P_{\text{high}}) \\ -\infty & \text{if } P_{\text{in}} \in (P_{\text{high}}, \infty) \end{cases}$$

(1)

- **Mode II:**

$$P_2 = P_{\text{in}};$$

$$P_{\text{reflected},2} = P_{\text{in}} - |\Gamma_2| = \begin{cases} P_2 & \text{if } P_{\text{in}} \in (\infty, P_{\text{low}}) \\ P_2 - |\Gamma_2| & \text{if } P_{\text{in}} \in (P_{\text{low}}, P_{\text{high}}) \\ -\infty & \text{if } P_{\text{in}} \in (P_{\text{high}}, \infty) \end{cases}$$

$$P_{\text{out},1} = -\infty \forall P_{\text{in}};$$

$$P_{\text{out},3} = P_{\text{in}} - |T_{32}| = \begin{cases} -\infty & \text{if } P_{\text{in}} \in (\infty, P_{\text{low}}) \\ P_2 - |T_{32}| & \text{if } P_{\text{in}} \in (P_{\text{low}}, P_{\text{high}}) \\ P_2 & \text{if } P_{\text{in}} \in (P_{\text{high}}, \infty) \end{cases}$$

(2)

- **Mode III:**

$$P_3 = P_{\text{in}};$$

$$P_{\text{out},1} = P_3 \forall P_{\text{in}};$$

$$P_{\text{out},2} = -\infty \forall P_{\text{in}};$$

where $P_1$, $P_2$, $P_3$, $P_{\text{out},1}$, $P_{\text{out},2}$, $P_{\text{out},3}$, $P_{\text{reflected},2}$, and $P_{\text{in}}$ (dBm) are the power values flowing into ports 1 to 3, power flowing out at ports 1 to 3, power reflected at port 2, and power of the incident signal, respectively.

Based on (1) and (2), at state I-M for the medium power level between $P_{\text{low}}$ and $P_{\text{high}}$, the signal flows out from both port 2 and port 3. In this case, the proposed network functions as a power divider with a controllable power output ratio $P_{\text{out},2}/P_{\text{out},3}$ modulated by the input power level. Considering state II-M, the signal will partly flow from port 2 to port 3 and partly be reflected, as expressed by $P_{\text{reflected},2}$. Consequently, the ratio $P_{\text{reflected},2}/P_{\text{out},3}$ is also adjustable as in state I-M.

As a proof of concept, the proposed network was designed and experimentally investigated at 4 GHz band with the thresholds $P_{\text{low}}$ and $P_{\text{high}}$ of $-20$ dBm and $+10$ dBm, respectively. Investigated prototype is constructed by incorporating previously mentioned power-dependent network with a circulator. The performance of the proposed BSRM network is measured with a Keysight N5227B PNA. Fig. 4(b)–(d) illustrate the measured reflection coefficient of each port at different power levels. The input power range is classified into three regimes, namely low, medium, and high. As can be observed, the measured reflection coefficients at port 1 and port 3 change only minimally with variation in the input power levels. Meanwhile, the measured reflection coefficients at port 2 vary significantly. Specifically, at 4.1 GHz,
the measured $S_{22}$ decreases from $-3.62$ to $-16.02$ dB when the incident power level is varied from $-30$ to $15$ dBm. This result is appropriate for the structure of the proposed network, as depicted in the equivalent circuit in Fig. 3. Owing to the existence of a power-dependent network in the connection between the circulator and port 2, this port has variable characteristics based on the input power. Meanwhile, the other ports are incapable of a similar functionality because the power-dependent network is not used with these ports.

In conclusion, a BSRM network that is controlled via RF power level and completely independent of supporting electronic devices or components can thus be achieved using variations in the diode impedances at different power levels and by incorporating a passive navigator. Owing to passive manipulation using the changes in the incident RF signal power levels, the proposed network achieves a dynamically self-reconfigurable operation with three states for each mode, as summarised in Table 2. Owing to the main features of a controllable output power ratio and signal flow, the most suitable applications would be the one whose performances are strongly related to power ratio of different channels, such as polarization reconfigurable antennas, beam-steering, beam-reconfigurable antenna arrays, or even further applied in amplitude modulation RF schematic. Despite of the

| Mode | Low power | Medium power | High power |
|------|-----------|--------------|------------|
| I    | Through from port 1-3 | Power divider with tunable $P_2/P_3$ | Through from port 1-2 |
| II   | Reflector | Power divider with tunable $P_2^*/P_3$ | Through from port 2-3 |
| III  | Through from port 3-1 | Through | Through from port 3-1 |

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FIGURE 6. Experimental investigation of the proposed BSRM network. (a) Operational illustration of the proposed structure for different modes and power levels. (b)–(d) Resulting powers of the proposed structure at Modes I, II, and III for different input power levels.

differences in initial design purposes, the proposed network also can used as a half-duplex SPDT to navigate the signals. In this scenario, the ideal mode is mode I. To avoid the consequences of leakage power toward the configuration that is not the best suited, the isolation between 2 channels should be at least 10 dB. Therefore, the best option is using two well-separated power levels which are totally in high or low power range. For the case of proposed BSRM network, the suitable power levels should be bigger than 15 dBm or lower than $-30$ dBm to achieve that acceptable isolation. To achieve better performance as a half-duplex SPDT, the proposed principle could be extended with more complicated power-dependent network which use multiple diodes or different matching topologies to increase the difference between the impedance of each power levels. As such, the isolation between different ports of designed network can be significantly enhanced. In addition, a more sensitive BSRM network with minimal power range for the reconfiguration can also be achieved by using the same method. However, in this proposed work, a wide power range from $-30$ dBm to 20 dBm is necessary to separate transmitting power and receiving power due to the fact that the receiving power is conventionally much less than $-30$ dBm whereas 20 dBm is typical transmitting power.

C. PURELY SELF-POLARISATION-RECONFIGURABLE (PSPR) ANTENNA

The function of a reconfigurable antenna can typically be switched using an external controller. However, when a two-port antenna is combined with the proposed BSRM network, its characteristics can be self-switched without any external electronic devices, such as a DC bias network or digital control via microcontroller. As a demonstration, a dual-feed microstrip patch antenna was built on a 1.2 mm thick FR4 substrate with a dielectric constant of $\varepsilon = 4.1$ and loss tangent of $\delta = 0.02$. The power-dependent portion of the BSRM network was constructed at port 1 of the antenna with a Schottky diode SMS7630, as demonstrated in Fig. 7(a). Consequently, port 1 of the proposed structure functioned as a power-dependent port, and the static navigator portion was handled by an external circulator. The polarisation was handled by a patch antenna with two perpendicular ports (Fig. 7(b)). Such a configuration is similar to the case in which ports 2 and 3 of the proposed BSRM network are
FIGURE 7. Proposed purely self-polarisation-reconfigurable (PSPR) antenna. (a) Perspective view of the proposed structure. (b) Electric field distributions of the patch antenna for different feeding positions. (c) Simulated 3D radiation pattern of the dual-feed patch antenna at 4.1 GHz. (d) Simulated and measured reflection coefficients of the dual-feed patch antenna (without the proposed power-dependent network). (e) Measured reflection coefficients of the proposed structure for the power-dependent port (port 1) at different power levels.

The simulated electric field distribution for each feeding position is depicted in Fig. 7(b). If the radiating patch is fed using port 1, the radiated electromagnetic (EM) wave has vertical polarisation (VP). Otherwise, it has horizontal polarisation (HP) if the radiating patch is fed using port 2. Fig. 7(c) presents the simulated 3D radiation patterns of the designed structure at 4.1 GHz. A full-wave analysis reveals that the designed patch antenna without the power-dependent network achieves a 10 dB impedance bandwidth in the range of 4.01–4.10 GHz, with a peak gain of 2.69 dBi at 4.1 GHz. The simulated and measured reflection coefficients of the designed patch antenna are in good agreement, as depicted in Fig. 7(d). In contrast, the measured reflection coefficients of the designed patch antenna with a power-dependent network at different power levels are presented in Fig. 7(e).

Because a dual-feed patch antenna is incorporated with the proposed BSRM network, the signal flows in the proposed PSPR antenna will be divided into two separate paths based on the power levels. By directing these signal flows to the designed dual-feed antenna, the radiated waves can be being self-manipulated using the power levels of the input signals. Ports 2 and 3 of the proposed BSRM network are connected to ports 1 and 2 of the patch radiated portions, respectively. At low input power (less than -20 dBm), the BSRM network is in state I-L (see Table 2 ); therefore, the signal will flow into port 2 of the antenna, and the EM wave is radiated with HP. Meanwhile, when the power of the incident signal exceeds the high-power threshold of 10 dBm, the BSRM network is in state I-H, the designed dual-feed patch antenna generates a VP wave because the signal flows to port 1 of the antenna. In contrast, when the proposed antenna functions as a receiver, the BSRM network acts only in state III-L because of the low power of the incoming signal.
FIGURE 8. (a) Geometry dimensions of proposed PSPR antenna. (b, c) Simulated reflection coefficients and peak gain of proposed design with different patch antenna sizes. (d, e) Simulated reflection coefficients of proposed design with different size of shorted stub which connects diode with the ground plane.

FIGURE 9. Experimental investigation of the proposed PSPR antenna. (a), (b) Configurations to investigate the operations of the proposed TX and RX antenna structures, respectively. (c), (d) Received power of the proposed structure with VP and HP EM waves, considered for the TX and RX states, respectively.

III. EXPERIMENTAL VERIFICATION

The self-polarisation-reconfiguration of the proposed PSPR antenna is experimentally investigated as depicted in Fig. 9(a) and 9(b). The measurements for the proposed structure are realised in two scenarios where the designed structure sequentially functions as a TX and RX antenna.
Further, for comparison, an SGH395 standard horn antenna manufactured by Microwave Vision Group is used and sequentially installed in the vertical and horizontal directions to create and track the VP and HP EM waves. The experiments were conducted using an Agilent N5182A vector signal generator and a HP 8593E spectrum analyser. Generated signals have a central frequency of 4.01 GHz with a transmission distance of $L = 4.1$ m. The experimental results illustrate a close agreement with the theoretically expected behaviours and the operational mechanism of the proposed PSPR antenna.

Fig. 9(c) illustrates the measured received power of the VP and HP horn antennas when the proposed structure functions as a TX antenna. For the same generated TX power in the low-power range (less than -20 dBm) and same distance between the TX and RX antennas, the received power of the HP horn antenna is higher than that of the VP antenna, with a difference of approximately 10 dB. This result indicates that the proposed structure functions as a HP antenna in the low-power range. With the increment of the input TX power, the difference between the HP and VP received powers decreases. The HP and VP received powers achieve balance near 3 dBm of input TX power. When the input TX power continues increasing and exceeds the high-power threshold of 10 dBm, the VP received power becomes higher than the HP received power. This result indicates that the proposed structure functions as a VP antenna in the high-power range. Because the maximum generated power from our signal generator is 17 dBm and the cable loss is 4.6 dB, measurements for TX power exceeding 12.4 dBm are not available.

When the proposed structure functions as an RX antenna, the standard horn antenna is sequentially installed as a TX antenna with vertical and horizontal directions to generate the respective polarisations of the EM wave. Because of the free-space path loss, the received power is less than $-20$ dBm. Consequently, this value of the received power maintains the proposed structure under its low-power state. As illustrated in Fig. 9(d), the measured received power of the proposed antenna exhibited a difference between the incoming HP and VP EM wave. The HP received power remained higher than the VP received power, with the highest difference of 16.41 dB at $-61.6$ dBm of received power. This result confirms that for low incident RF power, the proposed structure only functions as a HP antenna.

**IV. CONCLUSION**

We proposed a concept, strategy, and design for a novel all-passive batteryless self-reconfigurable multimode network to control the RF signal flow and ratio dynamically and automatically by manipulating only the power level of the incident signal without any additional supporting electronic components. Thanks to the power-dependence which is created by all-passively smart-sensing the power level, the dependence of the device on sensing electronic circuits is completely eliminated. The proposed network was theoretically and experimentally investigated to validate the operational mechanisms. Our proposed strategy is primarily based on ingeniously exploiting the characteristics of non-linear devices at different power levels to create impedance matching/mismatching states and integrating with non-reciprocal components. Consequently, the proposed network eliminates dependence on supporting electronic devices and achieves a highly flexible, all-passive, and dynamically self-controllable ability to manipulate RF signal flow and ratio with seven different sub-states corresponding to three input power level regimes. In the comparison with conventional actively controlling components which are typically used in RF systems, the proposed idea of a batteryless self-reconfigurable multimode network would bring considerable advantages to RF system, such as reducing the number of controlling signals, reducing the total consumed power, reducing the number of active components, and significantly simplifying the total design of an RF system.

By incorporating the proposed network in a dual-feed antenna, we demonstrated the applicability of the proposed structure in the design of the PSPR antenna, which can self-switch the polarisation between vertical and horizontal based on the input RF power level without any external electronic devices. The proposed idea is considerably useful when the difference in transmitting and receiving modes is necessary. For instance, proposed PSPR antenna can be applied to a polarisation encoding RFID chipless systems which would significantly enhance the coding efficiency owing to the polarisation diversity [57]. Instead of using complex reader systems with several antennas for transmitting/receiving or for different polarisations, using only one proposed PSPR antenna might be enough. Furthermore, since the proposed antenna is purely self-reconfigurable, there are completely no controlling, sensing, or DC power supplying components. Another application is backscatter-based communication system, in which the system needs to operate with different transmitting and receiving antennas [58]. In addition, the proposed idea can also be applied into electronic warfare system by incorporating with conventional methods of frequency hopping or spread spectrum. For examples, after processing with conventional methods, the transmitted signal be further periodically or randomly change its polarization following a pre-defined rules. By combining this technique with conventional mentioned methods, the levels of security can be considerably enhanced.

On the other hand, the proposed BSRM network can be extended to other radiating structures to achieve purely self-frequency and purely self-pattern reconfigurable antennas. The proposed scheme has the advantages of a unique, simple, and flexible structure compared with other reconfigurable techniques. Furthermore, the proposed BSRM is applicable not only to chipless purely self-reconfigurable antennas but also to other RF devices and systems.

In conclusion, the proposed work reveals a potential strategy for replacing traditional energy harvesters in RF networks for dynamically controlling RF signal flows and ratios without additional electronic components; this is expected to pave
a new path for purely self-reconfigurable or self-adaptive RF devices. With the proposed strategy, the field of reconfigurable devices and systems is now extendable and establishing an important milestone for the future development of small RF devices. The application of the proposed work is not only limited to antennas but also might be extendable to other RF self-adaptive devices, such as RF filters, switches, and phase shifters, and so on.

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