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Frequency- and Pattern-Reconfigurable Cone Antenna Based on Liquid Metal

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Abstract—A frequency- and pattern-reconfigurable cone antenna utilizing liquid metal is investigated. It contains a cone antenna, four reflectors, and a circular ground plane. The transparent resin is processed into a mold for the cone and reflective poles to store the liquid-metal. By controlling the poles height in the mold, the proposed antenna can realize four radiation patterns. Meanwhile, the cone height could be adjusted by the reflective poles, thereby achieving frequency tuning. The simulation and measurement results show that, by tuning and switching the liquid-metal radiator and reflectors, a wide frequency tuning bandwidth of 43.2% is achieved, and a pattern reconfigurable with five types of beam steering over 360° coverage is realized. The prototype is fabricated, assembled, and measured, with good agreement between the simulated and measured results. The design of indoor coverage antenna system must have comprehensive measurement indexes such as multi-bands, multi-beams, high gain, and low cost.

1. INTRODUCTION

With the explosion of information, the demand for mobile communication and wireless networks at different standards has highly increased as the most active daily equipment. Owing to market demand, reconfigurable antennas have attracted increasing attention. A frequency-reconfigurable antenna can provide the capability for an antenna to operate only in the preferred frequency band and reduce the complexity of hardware and the cost of the system [1]. Additionally, pattern-reconfigurable antennas have also attracted great interest owing to their advantage of reducing the interference from undesired directions, avoiding source noise, saving energy, and link reliability [2]. Some of the main design methods for pattern-reconfigurable and frequency-reconfigurable antennas have been designed and researched to meet different standards and applications [3, 5]. For example in [4], A compact frequency-reconfigurable slot antenna by inserting two PIN diodes inside the slots for switching the frequencies of 2.3 GHz, 4.5 GHz, and 5.8 GHz was proposed. In [6], a monopole antenna array with pairs of switchable parasitic strips was reported to realize eight beams for omnidirectional azimuth coverage.

However, most of designed antennas can only implement a reconfigurable mechanism. Frequency- and pattern-reconfigurable antennas were designed to meet the requirements of multifunctional ability in sensing, radar, and modern wireless communication systems [7–10]. In [7], a frequency- and pattern-reconfigurable two-element array antenna covered a relative frequency tuning range of 10% extending from 2.15 to 2.38 GHz, within which it presented a continuously beam-steerable radiation pattern covering scanning angles from −23° to +23° across the broadside. The frequency-tuning mechanism was implemented using varactor diodes loaded with open stubs. Two independent bias voltages allowed for the independent addition of pattern reconfigurability to the array. A frequency- and pattern-reconfigurable slot antenna was presented in [9], where two switches were placed in the slot to produce

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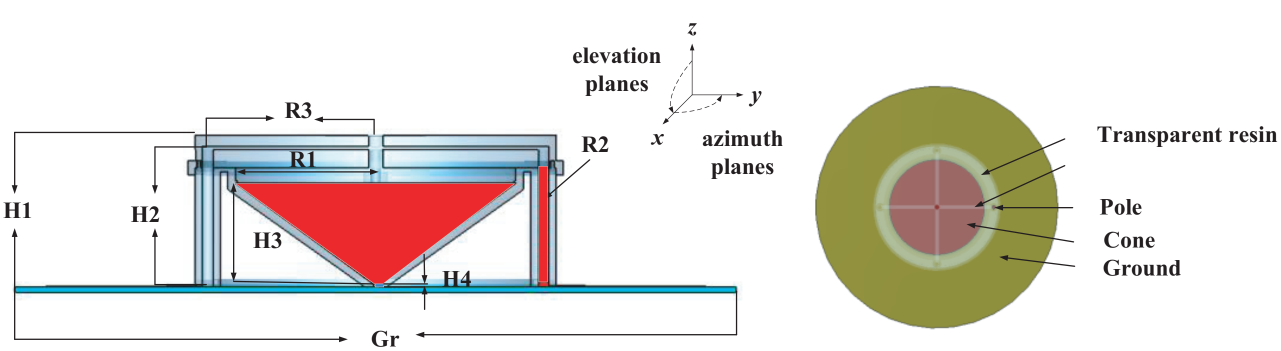
three reconfigurable frequency bands: at 1.82 GHz, 1.93 GHz, and 2.10 GHz. The introduction of four slits at the edge of the ground plane offered pattern reconfigurability at three angles (0°, −15° and +15°).

The designs mentioned above combine two types of reconfigurability based on switch chips, which have poor performance in the tuning range, structural complications, and mechanical failure. To obtain large linear tuning ranges and fast repair capabilities, liquid metal was applied as a new material to replace the variable reactive components [11–15]. A microfluidically frequency- and polarization-reconfigurable slot antenna using liquid metal (LM) was reported in [12], which had an overall tuning of 3 dB axial ratio bandwidth (ARBW) of 26.42% (2.3 to 3 GHz) and achieved the switch between left-hand circular polarization (LHCP), right-hand circular polarization (RHCP), and linear polarization by injecting LM into the +45° and −45° channels. Reference [13] presented a beamwidth-controllable impulse radiating antenna (IRA). The typical solid reflector of the IRA was replaced with a wired liquid-metal reflector with a bandwidth variation of up to 44%. To the best of the authors' knowledge, the proposed antenna has not achieved frequency and pattern-reconfiguration using liquid metal as a switching mechanism.

In this study, a simple cone antenna is presented for the first time, using the concept of manipulating liquid metal in 3D-printed microfluidic channels to realize beam steering and frequency adjustability. The proposed antenna provides continuous tuning in 1.27 to 1.97 GHz range with a tuning ratio of 1.55 : 1, by continuous movement of the liquid metal on the reflector poles. When the liquid metal is injected into the pole around the main radiator as a reflector, a radiation pattern containing five types of switched beams is obtained. The design is simple and has a compact structure suitable for multiple pieces of wireless communication equipment. Compared to other proposed solutions, this design provides a wider frequency-tuning range and multiple radiation patterns.

2. ANTENNA STRUCTURE

As Fig. 1 shows, the proposed frequency- and pattern-reconfigurable antenna mainly contains a transparent resin as the storage and control structure of the radiator, circular ground plane, and SMA connector. The printing model utilizes transparent photosensitive resin with a relative permittivity of 3.5, which has the advantages of a smooth surface, strong expression of details, high-quality waterproof ability, strong dimensional stability, and is almost colorless. The cone model is dugout at the center of the transparent resin model. Owing to the gradual change in the connection from the bottom to the top of the cone, the cone with the characteristics of the traveling wave has a wide bandwidth. Four poles around the cone are excavated in the model at a 90° interval. A cross-bridge type structure as a microfluidic channel is utilized to connect the cone and poles. Liquid metal is injected into poles and cone and is marked in dark red in Fig. 1. The feed distance H_4 between the ground plane and the bottom of the cone is connected to an SMA connector with conductive glue. The selected ground plane substrate is FR4 with relative dielectric constant of 4.4 and thickness of 1.5 mm. The final optimized parameters of the proposed antenna are listed in Table 1.



(a) (b)

Figure 1. The structure of the proposed frequency- and pattern-reconfigurable cone antenna: (a) cross section, (b) the top view.

Table 1. Final optimal dimension values of the proposed antenna.

Dimension	Value (mm)	Dimension	Value (mm)
G_r	200	H_1	42
R_1	38.9	H_2	38
R_2	1.5	H_3	29.6
R_3	46.6	H_4	0.8

3. DESIGN PRINCIPLE

3.1. Reconfigurable Principle

As a traveling-wave broadband antenna, frequency impedance of cone is as follows [16]:

$$\beta/\alpha = e^{-j2ka}\left\{\frac{1 + j\dfrac{\xi_0}{2\pi Z_c}\displaystyle\sum_{n=1,3,5\ldots}^{\infty}\frac{2n+1}{n(n+1)}\left[P_n(\cos\theta_0)\right]^2\xi_n(ka)}{1 - j\dfrac{\xi_0}{2\pi Z_c}\displaystyle\sum_{n=1,3,5\ldots}^{\infty}\frac{2n+1}{n(n+1)}\left[P_n(\cos\theta_0)\right]^2\xi_n(ka)}\right\} \tag{1}$$

When $30^\circ \leq \theta_0 \leq 90^\circ$

$$\xi_n(ka) = \frac{h_n^2(ka)}{h_{n-1}^2(ka) - \dfrac{n}{ka}h_n^2(ka)}$$

β/α is the ratio of reflection amplitude of TEM wave propagating outward in the antenna area, and $\xi_n(ka)$ is a real variable complex auxiliary function.

The impedance characteristics of the cone antenna are related to the effective length a and the strong angular θ dependence of the cone. In this study, the height of the cone, as an important adjustable parameter, is controlled by injecting liquid metal to realize frequency reconfiguration while keeping the cone angle unchanged. The frequency control process is shown in Fig. 2(a). The liquid metal is injected into the pole using syringes below the ground plane, which is beneficial for controlling the continuous change in the proposed antenna and does not interfere with the radiation of the cone. Subsequently, as the liquid metal flows from the microfluidic channel to the container of the cone under pressure, the height H_3 is adjusted to achieve frequency reconfigurability.

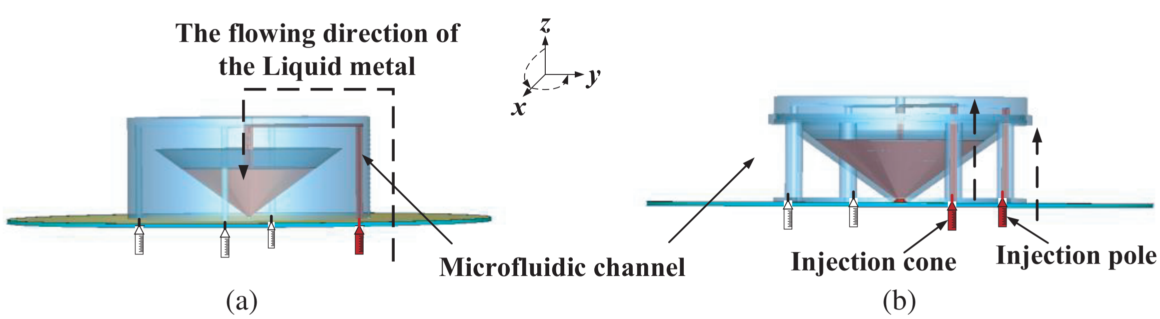


Figure 2. Design principle of proposed antenna: (a) frequency-reconfigurable antenna, (b) pattern-reconfigurable antenna.

Figure 2(b) shows the pattern-reconfigurable mechanism. Using the reflection principle of the Yagi antenna, a reconfigurable pattern is realized by adding multiple liquid-metal reflective poles around the cone. The passive reflector is slightly longer than half the operating wavelength, showing inductance relative to the radiator. The current of its induced electromagnetic wave lags behind the cone by about 180° resulting in the cancellation of the signal in the direction of the reflector and the deflection of the radiation direction in the opposite direction. The reflector can effectively eliminate the back lobe of the antenna pattern, enhance the sensitivity of the antenna to the front signal, and make the antenna have strong directivity and high gain.

3.2. Parameter Analysis

The high-frequency structure simulator (HFSS) is used to simulate and analyze the proposed antenna. Tunability of the antenna is achieved by adjusting the height of the cone, as shown in Fig. 3. As the liquid metal is poured into the cone, the radiator and frequency of the antenna are changed. In the circumstances, all reflector poles with empty states are used as the microfluidic channel, not as a part of radiation structure. When the height H_3 is selected as 28.8 mm, the scattering parameters is less than -10 dB between 1.23 GHz and 2.54 GHz. The frequency band moves to a higher frequency with a decrease in the height of the cone. The lowest cone with $H_3 = 16.8$ mm is operated in the frequency range from 2.09 GHz to 3.97 GHz. Consequently, the antenna operates in the frequency band range from 1.23 to 3.97 GHz with a tuning ratio of 1.7 : 1, and the impedance bandwidth of the cone is above 60% in all cone heights mentioned above.

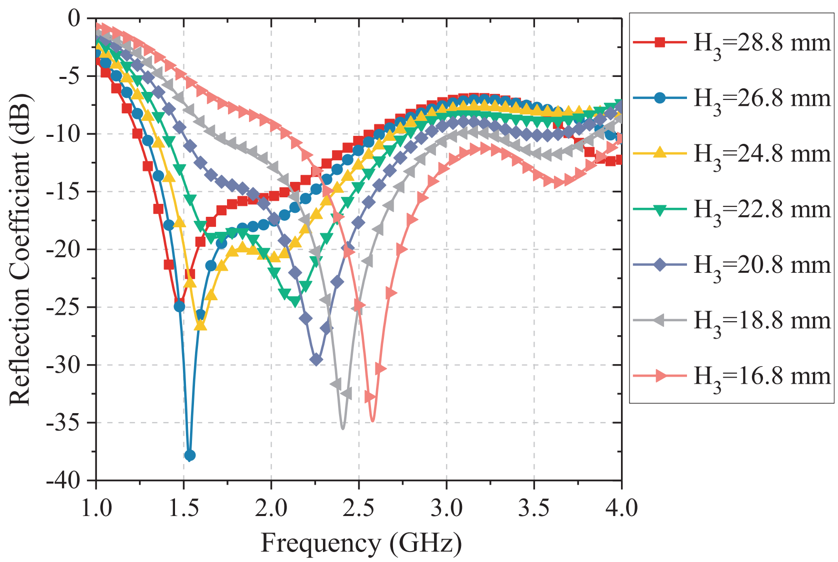


Figure 3. Simulated reflection coefficient of the proposed antenna at different H_3.

The effect of the reflector elements on the impedance bandwidth and radiation pattern is investigated in Table 2. When the liquid metal is injected into corner cone, the radiation pattern of proposed antenna is a typical vertical polarization. It can be observed that empty poles have hardly influenced the radiation pattern. The impedance bandwidth decreases from 69.5% to 62.7% because the matching is poor when the cone height decreases.

The effective BW ($S_{11} \leq -10$ dB) under the action of the reflective pole listed in Table 2 is narrower than the actual -10 dB impedance bandwidth (pattern deflection). This is because the radius of the pole is limited, which could only affect the radiation pattern in a finite impedance bandwidth. Simultaneously, the lower pole has a greater impact on the deflection of the high-frequency pattern. The beam widths of the antenna are 204.6°, 183.7°, 150.9°, and 118°, at 2 GHz with a decrease in the pole height from 33 mm to 20 mm. By controlling the liquid metal, cones of different heights corresponding to different reflectors produce a deflection of the pattern in different frequency bands. There are several choices between cone height and pole height, which are listed in the above table for reference.

Table 2. States of liquid metal, impedance bandwidth, beam width and main-lobe direction at different cone height.

Cone Height H_3 (mm)	No pole	With liquid-metal pole			
	BW (%)	Pole height H_2 (mm)	Effective BW (%)	-10 dB BW (%)	Beam width (°)
28.8	69.5	33	50	65.2	204.6
24.8	67.6	29	43.9	61.5	183.7
20.8	63.9	27	32.5	58.4	150.9
16.8	62.7	20	26.1	66.6	118

4. SIMULATION AND MEASURED RESULTS

4.1. Return Loss

Finally, a frequency- and pattern-reconfigurable cone antenna based on liquid metal is manufactured and measured in Fig. 4. The antenna structure consists of transparent resin and FR4 plate. The coaxial feed is connected between the ground plane and the bottom of the cone. The liquid metal as the radiation structure and the controllable part is controlled by a needle tube. A liquid metal eutectic gallium-indium (EGaIn; 75% gallium, 25% indium) with relatively good electrical conductivity ($\sigma = 3.46 \times 10^6$ S/m) is used as the radiation part of the antenna, which is nontoxic compared to liquid mercury. The return losses are measured using an Agilent N5230C vector network analyzer (VNA). When the reflective pole is added, the return loss is greater than 10 dB from 1.27 GHz to 4 GHz. It can be observed that when injecting the liquid metal into cone with a height of 28.8 mm, 24.8 mm, 20.8 mm, and 16.8 mm, an impedance bandwidth of 103%, 100%, 90.9%, 68% successfully covers Bluetooth, WiMAX, and WLAN bands, respectively. The proposed cone provides continuous tuning in the 1.27–1.97 GHz range with a tuning ratio of 1.55 : 1. The trend of the curves and the lowest resonance frequency of the antenna are the same as those of the simulation results, and the measured impedance matched better. Owing to the instability of the liquid metal surface caused by hand shaking during the test, the control accuracy of liquid metal, antenna installation, and the test error of the line loss and connection head, there will be some deviation which will impact the impedance matching and S parameters of proposed antenna.

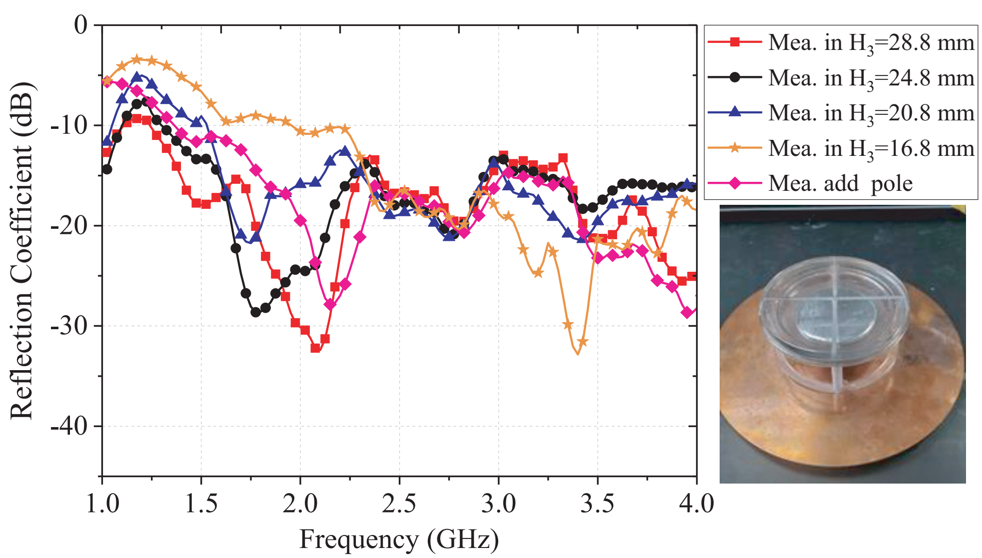


Figure 4. The measured results of the fabricated reconfigurable antenna.

4.2. Radiation Patterns and Polarization

Taking the antenna heights of $H_3 = 28.8\,\text{mm}$ and $H_2 = 33\,\text{mm}$ as a point of reference, an anechoic chamber is used to measure the radiation patterns of the proposed cone-shaped antenna in five pattern configurations in Fig. 5. Mode 1 is omnidirectional radiation without a liquid-metal reflector pole. The radiation patterns of modes 2, 3, 4, and 5 indicate that a reflector pole is added in different azimuth planes at 90° intervals, which is reflected in the opposite direction of the pole. Notably, the experimental results are compatible with the simulation results in all the modes at 2 GHz. The measured maximum gain values are 5.47 dB, 6.39 dB, 6.32 dB, 6.10 dB, and 6.02 dB at Mode 1, Mode 2, Mode 3, Mode 4, and Mode 5 at 2 GHz, respectively. The maximum test gain is 8.21 dB.

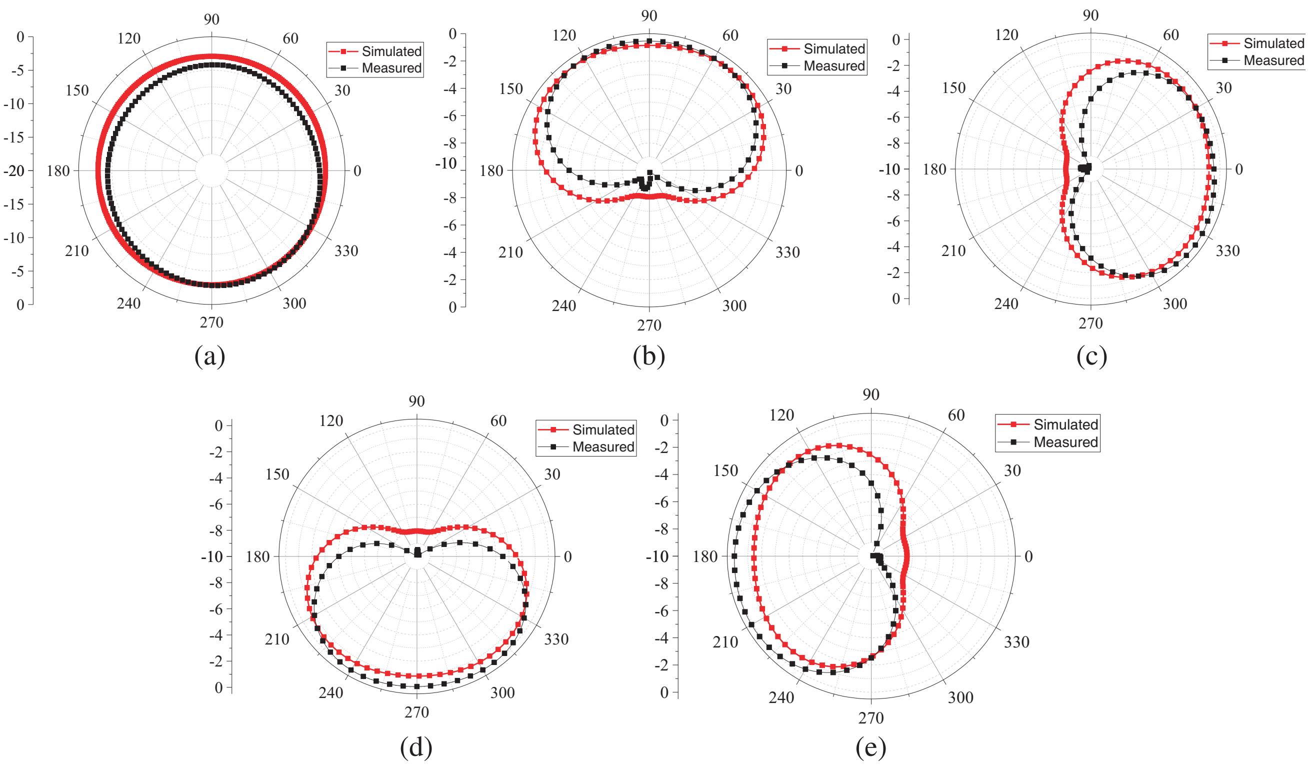


Figure 5. Simulated and measured radiation patterns of antenna in the E-plane at 2 GHz: (a) Mode 1, (b) Mode 2, (c) Mode 3, (d) Mode 4, (e) Mode 5.

5. CONCLUSIONS

A pattern-reconfigurable and frequency-reconfigurable antenna that applies liquid metal is proposed. The frequency-tuning characteristics of a dynamically adjustable liquid-metal cone are realized. Further, multiple directional patterns can be reconfigured by adding liquid metal reflectors. A switching mechanism of radiation structure and switching structure controlled by liquid metal is designed, manufactured, and realized to verify the basic concept of the proposed design. It achieves a maximum tuning bandwidth of 43.2% for five types of beams. The proposed antenna has the potential to produce more frequency- and pattern-reconfigurable bands. The antenna is suitable for integration into smart indoor roof antenna networking applications, particularly when the pattern is required to switch between unidirectional and omnidirectional operations.

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REFERENCES

1. Choukiker, Y. K. and S. K. Behera, "Wideband frequency reconfigurable Koch snowflake fractal antenna," *IET Microwaves Antennas Propag.*, Vol. 11, 203–208, 2017.
2. Shi, S. J. and W. P. Ding, "Radiation pattern reconfigurable microstrip antenna for WiMAX application," *Electro. Lett.*, Vol. 51, 662–664, 2015.
3. Nie, Z. H., H. Q. Zhai, L. H. Liu, J. X. Li, D. W. Hu, and J. H. Shi, "A dual-polarized frequency-reconfigurable low-profile antenna with harmonic suppression for 5G application," *IEEE Antennas Wireless Propag. Lett.*, Vol. 18, 1228–1232, 2019.
4. Han, L. P., C. X. Wang, X. W. Chen, and W. M. Zhang, "Compact frequency-reconfigurable slot antenna for wireless applications," *IEEE Antennas Wireless Propag. Lett.*, Vol. 15, 1795–1798, 2016.
5. Zhang, L., S. Gao, Q. Luo, P. R. Young, and Q. Li, "Planar ultrathin small beam-switching antenna," *IEEE Trans. Antennas Propag.*, Vol. 64, 5054–5063, 2016.
6. Juan, Y., W. Che, W. Yang, and Z. Chen, "Compact pattern-reconfigurable monopole antenna using parasitic strips," *IEEE Antennas Wireless Propag. Lett.*, Vol. 16, 557–560, 2017.
7. Siti, N. M. Z., N. T. Nghia, and C. Fumeaux, "A frequency- and pattern-reconfigurable two-element array antenna," *IEEE Antennas Wireless Propag. Lett.*, Vol. 15, 617–620, 2018.
8. Trong, N. N., L. Hall, and C. Fumeaux, "A frequency- and pattern-reconfigurable center-shorted microstrip antenna," *IEEE Antennas Wireless Propag. Lett.*, Vol. 15, 1955–1958, 2016.
9. Majid, H. A., M. K. A. Rahim, M. R. Hamid, and Mu. F. Ismail, "Frequency and pattern reconfigurable slot antenna," *IEEE Trans. Antennas Propag.*, Vol. 62, 5339–5343, 2014.
10. Li, P. K., Z. H. Shao, Q. Wang, and Y. J. Cheng, "Frequency- and pattern-reconfigurable antenna for multistandard wireless applications," *IEEE Antennas Wireless Propag. Lett.*, Vol. 14, 333–336, 2015.
11. Moorefield, M., R. Ordonez, A. Morishita, J. Dang, A. Ohta, and W. Shiroma, "Frequency-tunable patch antenna with liquid-metal-actuated loading slot," *Electro. Lett.*, Vol. 52, 498–500, 2016.
12. Liu, Y., Q. Wang, Y. T. Jia, and P. Zhu, "A frequency- and polarization-reconfigurable slot antenna using liquid metal," *IEEE Trans. Antennas Propag.*, Vol. 68, 7630–7635, 2020.
13. Ha, A., M. H. Chae, and K. Kim, "Beamwidth control of an impulse radiating antenna using a liquid metal reflector," *IEEE Antennas Wireless Propag. Lett.*, Vol. 4, 571–575, 2019.
14. Bai, X., M. Su, and Y. L. Wu, "Wideband pattern-reconfigurable cone antenna employing liquid metal reflectors," *IEEE Antennas Wireless Propag. Lett.*, Vol. 17, 916–919, 2018.
15. Murray, R. and R. Franklin, "Independently tunable annular slot antenna resonant frequencies using fluids," *IEEE Antennas Wireless Propag. Lett.*, Vol. 13, 1449–1452, 2014.
16. "Biconical television antenna," *Electrical Engineering*, Vol. 66, 1011–1011, 1947.