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Liquid Antennas: Past, Present and Future

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ABSTRACT The liquid antenna, as a new member of the antenna family, has drawn significant and increasing attention from both academia and industry due to its unique features. In this paper, a comprehensive review on this technology is presented which covers both metallic and non-metallic liquid antennas. Non-metallic liquid antennas are further divided into water-based and non-water-based liquid antennas. We first review and compare different liquid antennas and highlight the major developments in the past. Detailed discussions on state-of-the-art designs and current technical challenges are then presented, and finally the ways forward for the future are suggested. As a special feature, an in-depth review and discussion on materials for liquid antennas are provided which was not well covered in the literature in the past, important properties of selected materials are given in three comparison tables which can serve as antenna material selection references. It is shown that Galinstan is probably the best choice for metallic liquid antennas while ionic liquid materials are the preferred choice for dielectric liquid antennas. The challenges of making the liquid antenna for real-world applications are identified and discussed. It is believed that a liquid antenna implemented in radio systems is probably just around the corner.

INDEX TERMS Antennas, antenna designs, liquid antennas, liquid materials, reconfigurable antennas.

I. INTRODUCTION

AN ANTENNA is a critical component in radio communications and radar systems as it can transmit and/or receive electromagnetic signals efficiently and act as the interface between circuits and radio waves. The antenna performance makes a direct and major impact on the system performance. Antennas are traditionally made of metal to meet various requirements. As time goes by, the limitations of the conventional metal antenna for some applications gradually became apparent, and alternative antennas have therefore been proposed.

For example, dielectric resonant antennas (DRAs) were introduced in 1980s [1]. The original intention was to deal with the possible high loss of metal antennas at high frequencies (around mm-wave at the time), and later it was found that DRAs are also suitable for lower frequencies (several GHz) with a relatively compact size and low cost [2]. Thus, DRAs have found many real-world applications.

Liquid metal antennas, as another alternative, were introduced in 1990s when people wanted to make flexible and even reconfigurable antennas [3], [4], mercury was the obvious choice for such an application, however, it is toxic and expensive, thus, it is not suitable for practical applications. Since the liquid (metallic and non-metallic) antenna can offer many attractive and unique features (e.g., the reconfigurability and flexibility), withstand mechanical deformation (such as bending, stretching, folding, and twisting when used in a flexible substrate or holder) and are able to return to their original shape due to its highly reversible nature, thus, it has attracted a significant and growing attention for the past 20 years [5].

It is interesting to note that water was first employed to make an antenna in 1999 [6] – because the researchers found it hard to make their complex DRA prototype using solid materials in the lab. They soon realized the many advantages of using water to make a DRA: "the dielectric can easily be constrained to the desired shape; there are no airgaps between the probe and the dielectric, or between the dielectric and the conducting plane; when dealing with physically large DRAs at low frequencies, water is a low cost and readily accessible material with a high dielectric constant." Since then, the interest in developing liquid antennas has been growing steadily [7]–[24], because it has been gradually realized the potential benefits of the liquid antenna which is not just another DRA, but an antenna may offer what a conventional solid DRA cannot offer.

Today, we can find over 1700 publications on liquid antennas in the IEEE Xplore, of which over 440 are journal papers. There have been a lot of interesting developments and innovative designs in this area. However, there has been very little work on summarizing and analyzing these activities. A major effort is the recently published paper [24] which has reviewed over 100 papers but limited to reconfigurable liquid antennas. Thus, it is the right time to have a critical and in-depth review on liquid antennas, not just about what has been done, but more importantly about the technologies and challenges.

The main objective of this paper is therefore to *conduct a comprehensive review on various liquid antennas (not limited to reconfigurable antennas) and related materials, highlight the major developments in the past, discuss current state-of-the-art antenna designs and technologies, and then identify the best possible ways forward for the future.*

The rest of the paper is structured as follows. Section II is to classify liquid antennas in order to extract the common features of each group. Section III presents the study on liquid antenna materials which are classified as metallic and non-metallic, water-based and non-water-based liquids. Section IV is to review liquid metal antennas where the pros and cons are summarized. Section V is focused on water-based antennas: both conductive and non-conductive antennas are examined. Non-water-based liquid antennas are introduced and discussed in Section VI. Some novel antenna examples are also presented in this section to demonstrate the usefulness and special features of new liquid antennas. Section VII highlights the major advantages of liquid antennas. A comparison of various liquid antennas with the conventional antenna is provided. A detailed discussion on technical challenges is also presented. It is concluded with our views on the future research directions and potential applications.

II. LIQUID ANTENNA CLASSIFICATION

Liquid antennas are a relatively new type of antennas, unlike the conventional metal antennas and DRAs, they are made of liquid and a dielectric container/holder may be required (but not always). Many liquid antennas have been designed, made and tested. They could be categorized in different ways in order to better study their special features. For example, some people have divided them into conductive antennas and non-conductive antennas, or liquid DRAs and liquid-assisted antennas (which are hybrid antennas formed by liquid and metal antennas). In this paper we divide them into metallic and non-metallic liquid antennas, and the latter are further divided into water-based and non-water-based antennas as shown Fig. 1. We will use this classification to study the antennas in each category and identify their special features, advantages and disadvantages.

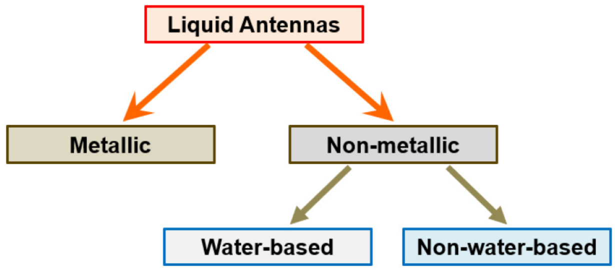


FIGURE 1. Classification of liquid antennas.

It should be pointed out that metallic liquid materials are conductive while non-metallic liquid materials could be conductive or non-conductive – this will be further discussed in the next sections. Water-based materials have been most widely used for making liquid antennas, the main reason is due to their easy accessibility and low-cost, not their performance. As shown in the next section, a recent study on liquid materials has revealed that better dielectric liquid materials (than water) for antennas are developed.

III. LIQUID MATERIALS FOR ANTENNAS

Liquid materials are the foundation for developing good liquid antennas: different material properties may lead to different antenna designs, performances, and applications. The main material properties of interest to us are the permittivity, conductivity, and permeability (the relative permeability of almost all liquid materials is 1 except some ferrofluids having a relative permeability of 2-3, thus the permeability is not discussed here). These electromagnetic (EM) properties are functions of frequency and temperature. The mechanical, chemical, and other relevant parameters (including cost) should also be considered when selecting the right material for making the antenna.

A. METALLIC LIQUIDS

The most well-known metallic liquid is mercury (Hg), which is the only metal in liquid form at room temperature with a melting point of −39 °C, but it is toxic and expensive. Alternative metallic liquid materials are mostly composites/alloys formed by conductive nanoparticles in less conductive fluids. Mercury can be used for creating liquid alloys, but gallium-based alloys show excellent thermal and electrical conductivities with low viscosity and non-toxicity. Their melting points are either lower than or close to room temperature [25]. For example, eutectic gallium indium alloy, EGaIn (75% Ga and 25% In), has a melting point of 16 °C and an electrical conductivity of 3.4×10^6 S/m (note: it is 58×10^6 S/m for copper) [18], [25], [26]. Once exposed to air, this liquid alloy reacts with oxygen to form a thin surface oxide layer, which improves mechanical stability and significantly prevents evaporation. Such advantages improve the performance of EGaIn in flexible liquid antennas without affecting the overall conductivity and antenna efficiency. Galinstan is another liquid metal alloy recently used for making foldable and stretchable antennas [5], [11], [27], which comprises of 68.5% gallium, 21.5% indium and 10% tin. It has similar performance and features as EGaIn but has a lower melting point (−19 °C) which makes it more attractive for real-world applications. There are other liquid metal materials (but not many) suitable for making antennas, for example, the $GaIn_{10}$ ink which is another conductive fluid composed of 90% gallium, 10% indium and approximately 0.026% oxygen (to make it viscous enough to be used as an ink) [28], and carbon nanotube or metal nanoparticle-based fluids are also new metallic liquid materials. EGaIn particles were used to create soft circuit boards, and to inject and sinter these particles in microchannels to form conductive pathways that can serve as antennas with tunable frequencies [29]. Silver nano-ink has been employed for printing antennas, but its melting point is high and becomes dry at room temperature [30]. The conductivity of these liquid metals is typically in the order of 10^6 S/m, which is large enough to realize high radiation efficiency when used as antenna materials. The summary of the most popular metallic liquid materials for antennas is given in Table 1, which shows their conductivities, compositions and melting points. The stability and cost for most of them are comparable. The thermal conductivity of these materials is far superior to ordinary non-metallic liquids. The selections are limited, a clear winner seems to be Galinstan in this category.

TABLE 1. Properties of popular metallic liquid materials.

	Conductivity (S/m)	Composition	Melting point (ºC)
Mercury	1.0×10^6	High purity Hg	-39
EGaIn	3.4×10^6	75% Ga 25% In	16
Galinstan	3.3×10^6	68.5% Ga, 21.5% In 10% Sn	-19
$GaIn_{10}$ Ink	3.0×10^6	~ 90% Ga, ~10% In, 0.026% O	16
EGaIn nanoparticles	0.092×10^6	EGaIn nanoparticles in PDMS substrate	About 16
Silver nano-ink	20×10^6	72 % Ag in organic solvent	961.78

TABLE 2. Water-based liquid properties (1 GHz, room temperature).

	ε_r'	Loss tangent	Freezing point ºC	Notes
Pure water	78	0.05	0	EM properties are sensitive to temperature and frequency. 81 is often used as water relative permittivity
Sea water (salinity 3.5%)	74	0.85	About -2.6	
Saline water (salinity 5%)	65	2.2	-2.5 ~ -3	
Dead sea water (saturated)	18	17.15	-32	
Water with 5% PG	77.5	0.06	-2 ~ -4	
Water with 30% PG	67.8	0.14	-11 ~ -12	
Water with 50% PG	55.3	0.23	-58~ -59	
Water with 5% Ethanol	77	0.05	-2 ~ -4	
Water with 30% Ethanol	63.6	0.11	-15	
Water with 50% Ethanol	49.1	0.17	-32	

B. NON-METALLIC LIQUIDS: WATER-BASED

Water is the most popular liquid on Earth, plentiful and easily accessible. Water-based liquids could be pure (or distilled) water, tap water, saline (or salty) water, and sea water. For simplicity, we can just divide them into pure water (no salt) and saline water (with different percentages of salt). Thus, tap water is considered as pure water while sea water is considered as a special saline water.

For antenna applications, a major drawback of water is that its EM properties are sensitive to temperature. When temperature is below 0 °C, it becomes ice which is solid and has very different EM properties and physical size. Saline water is better but offers limited improvement (depending on the percentage of salt, it can maintain as liquid down to −32 °C when saturated). A mixture of water and propylene glycol (PG, as an anti-freezer) can produce a lower freezing point (= melting point) [31]. The value decreases with the increase of PG percentage. The mixture can remain liquid down to −55 °C when the PG concentration reaches 70%. The PG is effective to reduce the freezing point of the water mixture, but it increases the loss tangent and affects the antenna efficiency. Similar trends can be found when water is mixed with ethanol. The relative permittivity ε_r', loss tangent and freezing point temperature of these materials are given in Table 2. Most of their freezing points are just slightly below 0 °C. A common problem of these liquids is that their EM properties are sensitive to temperature and frequency as shown in Fig. 2 (note: loss tan $\delta = \varepsilon_r''/\varepsilon_r' = \sigma/\omega\varepsilon$) – this property of water applies to most water-based liquids [32]. Their boiling points are around 100 °C. Overall, water with 5 – 10% of PG seems to be the best candidate for making antennas in this category.

C. NON-METALLIC LIQUIDS: NON-WATER-BASED

To find better liquids for antennas, many non-water-based liquids have been investigated [33], [34] which include ionic liquids, low-loss organic solvents (such as ethyl acetate, acetone), and various oils (e.g., mineral/ transformer oil). The electrical conductivities of most of them are found to be less than 0.001 S/m, and their relative permittivity are typically from 2 to about 30 over a large frequency range. Most importantly, their material properties are much more stable against

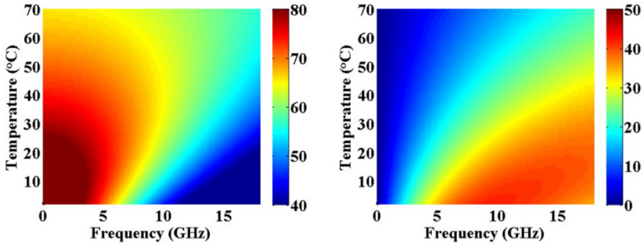


FIGURE 2. Relative complex permittivity ε_r of pure water as a function of frequency and temperature: (a) real part (ε_r'); (b) imaginary part (ε_r'') [32].

TABLE 3. Non-water-based liquid properties (1 GHz, room temperature).

	ε_r'	Loss tangent	Liquid range (°C)	Stability
Ethyl acetate (solvent)	~7	~0.02	-84 to 77	Easily evaporate
Acetone (solvent)	~20	~0.03	-84 to 56	Easily evaporate
Acetonitrile (solvent)	~38	~0.04	-45 to 82	Easily evaporate
Transformer oil	~3	~0.02	-45 to 250	Flammable
Choline L-alanine (Ionic liquid)	~12	~0.01	-56 to 186	Stable
T-chloride (Ionic liquid)	~2	~0.01	-70 to 118	Stable

temperature and frequency variations than water-based materials. For example, ethyl acetate is a liquid organic solvent, its relative permittivity is around 7 and the loss tangent < 0.04. In terms of the thermal effects, ethyl acetate has stable performance until 50 °C, and its freezing point is below −20 °C. Oils could also be used to make antennas, but their relative permittivities are relatively small (typically around 2) and may not be ideal for many antennas. Both solvents and oils may have a wider liquid range when compared with water, but generally they are not considered safe or environmentally friendly, because they are often flammable, volatile at elevated temperatures and cause safety concerns in high power applications.

Ionic liquids, as a very new material for RF/microwave applications, could become excellent candidates to address the above-mentioned limitations of water-based liquid materials. Ionic liquids have excellent material properties in terms of thermal stability, extremely low vapor pressures, reconfigurable electric conductivity, large electrochemical windows, high heat capacity, and nonflammability [34]. Room temperature ionic liquids usually consist of bulky asymmetric organic cations, most often paired with inorganic anions. A comprehensive measurement campaign was conducted at Liverpool University over the past 3 years and the EM properties of over 70 ionic liquids (relative permittivity and loss tangent) were obtained and summarized in [33] which could be used as a material library and look-up table when looking for ionic liquids for EM applications. The measured results demonstrated that ionic liquids had a wide selectable relative permittivity range from about 2 to 30ish whilst their loss tangent can be kept very small, down to 0.001 (for up to 18 GHz). This implies that some ionic liquids have shown excellent EM properties. In addition, it was found that some ionic liquids had very low freezing points (< -50 °C) and low vapor pressures [33], [34]. Unlike water-based liquids, the EM properties of ionic liquids are not sensitive to frequency and temperature changes, thus they can indeed be an excellent choice for making liquid antennas. The comparison of selected non-water-based dielectric liquids (including solvent, oil and ionic liquids) is provided in Table 3, in which the relative permittivity, loss tangent, liquid range, and material stability are presented. Trihexyltetradecylphosphonium chloride (T-chloride for short) is selected as a representative of the low permittivity and low loss ionic liquids. The costs of these materials are reasonable. Their liquid temperature range is typically from −50 °C to + 70 °C, which is suitable for most application environments.

The conductivity of solvents and oils is very low (typically between 10^{-3} and 10^{-9} S/m). The presence of acids, bases, salts, and dissolved carbon dioxide may increase their conductivity. For ionic liquids, the low-loss candidates have a comparable conductivity to solvents. There are some relatively conductive ionic liquid materials, such as C2MIM N(CN)2 (1-ethyl-3-methylimidazolium dicyanamide) whose conductivity is 2.83 S/m, comparable to that of the saline water [32]. The highest one we found is a PEDOT:PSS:RTIL mixture with a conductivity of 13600 S/m, thus, it is possible to use such a non-metallic liquid to make conductive liquid antennas which is an area of considerable interest but yet to be properly investigated and explored.

For non-metallic low-loss liquid materials, the recommended liquids are Choline L-alanine for high permittivity and T-chloride for low permittivity applications due to their overall performance as shown in Table 3.

IV. LIQUID METAL ANTENNAS

Unlike a conventional rigid metal antenna, a liquid metal antenna is physically flexible and/or reconfigurable in general. An early example of liquid metal antennas was a patch antenna made of mercury in 2004 [4]. Although this antenna achieved comparable performance as a traditional patch antenna, it has never been used for applications due to the toxic nature of mercury. Around year 2008, EGaIn was discovered as a safer liquid metal alloy with stable performance at room temperature, and it was then applied to various antenna designs [25], [26]. Examples include a foldable and stretchable liquid metal planar cone antenna using EGaIn and Polydimethylsiloxane (PDMS) substrate [27], a flexible liquid metal alloy microstrip patch antenna [35], and a liquid metal reconfigurable dipole antenna [36]. The unique advantages of liquid metal have been well utilized in these designs and they are patterned on highly flexible and stretchable substrate materials to realize excellent mechanical recognizability and EM performance. Microfluidic technology and liquid pumps have recently been combined with liquid metal to develop reconfigurable liquid antennas [18]. The fluidic metal could travel freely within the liquid channel, thereby significantly modifying the shape of the antenna. This cannot be realized in conventional solid metal antennas. Beam steering [13], frequency reconfigurable [18], [36], [37], and pattern reconfigurable [13], [38] liquid metal antennas have been reported. Two liquid metal antenna examples are provided in Fig. 3: (a) shows a liquid metal antenna with reconfigurable and steerable beams which can be effectively steered over the horizontal plane from 0 to 360 degrees, whilst the antenna also achieved radiation efficiency over 80% at 1.8 GHz in all reconfigurable cases [13]; (b) is a monopole antenna based on simple configurations using microfluidic channel and liquid metal (Hg in this case) pumping technology [18] which resulted in an extremely wide frequency tuning range from 1.29 to 5.17 GHz (1:4 ratio) and high efficiency (above 85%) over the frequency band. Compared with electrically tunable antennas, the reconfigurable liquid metal antennas using microfluidic channels and a liquid pump have a higher total efficiency as they do not suffer from the loss due to active switches and diodes. Moreover, the tuning range in terms of frequency and radiation pattern of liquid metal antennas is much wider than that of the traditional antennas due to the more flexible antenna structure variation.

The drawbacks of liquid metal antennas are that the fabrication process is normally more complicated than the conventional one, and the time response of the pump-based tunable system is much slower than that of the electrical tuning system which is usually done via a PIN switch. Furthermore, additional space is required for the liquid pump and microfluidic channel configurations, which may increase the overall antenna size and complexity for real-world applications.

Apart from the microfluidic channels, liquid metal antennas could also be encapsulated by the substrate or be sprayed onto the surface of the designed substrate [37], [39], [40]. Typical rigid substrate materials (such as Rogers RT Duroid 5880) have been used to hold liquid metal radiating structures [37]. Flexible substrate materials (such as PDMS [41], silicone rubber [42], and thermoplastic polyurethane (TPU) based NinjaFlex [43]) are commercially available to form the antenna substrate or microfluidic liquid channels with the aid of additive manufacturing technologies (e.g., 3D printing). Moreover, some state-of-the-art techniques have shown the feasibility of direct writing and printing of conductive fluids on substrates with either 2D or 3D structures in high resolution [44].

In [45], a liquid alloy spiral antenna was hosted by a PDMS dome-shaped substrate, the liquid alloy (Galinstan) was injected into the microfluidic channel network in the silicone with a syringe. The tunability of this antenna was not achieved by manipulating the liquid flow inside the channel, but instead by using a pneumatic pump to vary the height of the dome structure to change the antenna operating frequency (See Fig. 4). This antenna is electrically small

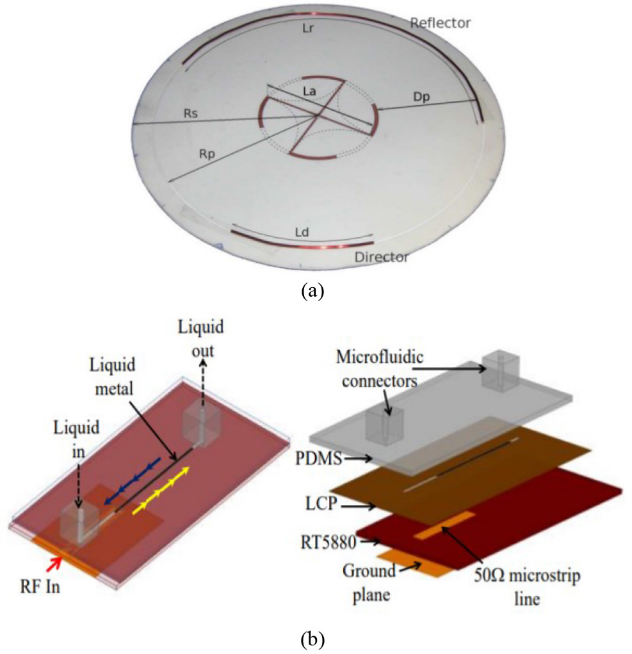


FIGURE 3. **(a) Pattern reconfigurable and beam steam liquid metal antenna [13]; (b) Frequency reconfigurable liquid metal monopole antenna [18].**

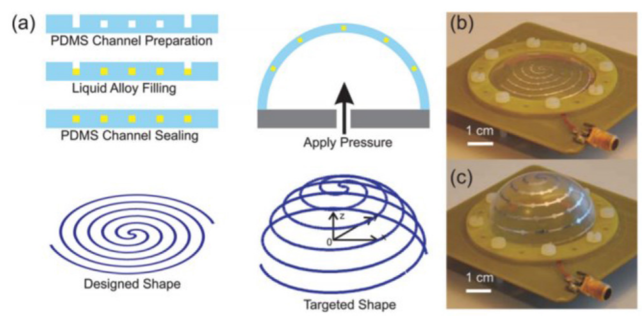
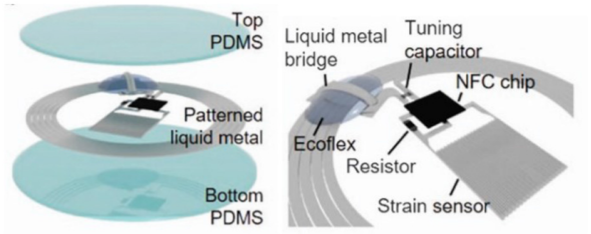


FIGURE 4. **(a) Schematic illustration of the implementation of the antenna using Galinstan alloy and PDMS antenna substrate. (b) and (c) Photos of the tunable spherical cap antenna at two typical working situations [45].**

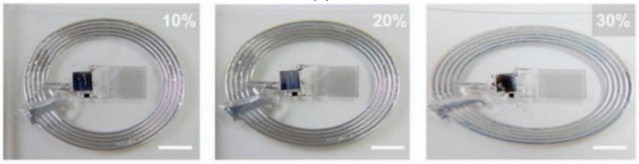
and could be tuned from 426 to 542 MHz. It demonstrated excellent mechanical stretchability and reconfigurability of liquid metal antennas using flexible metal and substrates.

Due to the non-toxic nature of liquid metal alloys (like EGaIn and Galinstan) and the availability of biocompatible and stretchable elastomer materials (such as PDMS), liquid metal antennas are particularly suitable for wearable and implantable applications in which the antenna structures need to conform to body skin and have the capability to overcome mechanical deformation during movements [46]. Liquid metal printed wireless sensor tags and wireless power transfer coils have been developed to take advantage of the abovementioned features of flexible liquid metal antennas [47], [48].

In [49], liquid metal alloy (Galinstan) was used to build a fully integrated flexible electronic system which includes an NFC antenna and strain sensors. The liquid metal has been



(a)



(b)

FIGURE 5. **(a) Magnified schematic illustration of the liquid-metal NFC device with antenna, NFC chip and strain sensors. (b) Demonstration of the stretchability of the liquid metal based wearable device [49].**

printed and sandwiched between two PDMS layers to form a skin-attachable and stretchable sensor for human motion monitoring as shown in Fig. 5. It is a near-field coil-based antenna operating at 13.56 MHz. This work has demonstrated a real-world application of liquid metal antennas in flexible and wearable electronic systems.

V. WATER-BASED LIQUID ANTENNAS

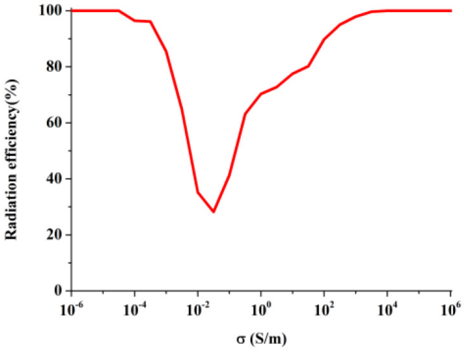
Water-based liquids are generally of low conductivity and high permittivity as we have seen in Table 2. They are suitable for a DRA or a hybrid antenna formed by a metal antenna loaded with the liquid (mainly to increase the bandwidth and reduce the antenna size), In addition to the flexibility and reconfigurability, they offer other benefits which metallic liquid antennas do not have, such as: a) cost-effective, eco-friendly and readily accessible (hence the myriad of antennas in this category); b) compact size because the antenna size could be reduced by a factor of $\sqrt{\varepsilon_r}$; c) a small radar cross section (RCS) if the liquid is drained when not in operation; d) transparency – this is attractive for the application that the antenna should be invisible or not obvious. Two types of water-based liquid antennas have been investigated: saline water antennas [12], [14], [50]–[59] and pure water antennas [15]–[17], [60]–[70] which are discussed in the coming two sub-sections.

A. SALINE WATER ANTENNAS

Sea water can be considered as natural saline water and has been widely used for liquid antenna research due to its availability and potential marine-related applications. The most well-known example is the monopole antenna developed by a U.S. navy research center as shown in Fig. 6. It was a frequency reconfigurable sea water antenna and tested at a distance over 30 miles using frequencies ranging from 2 to 400 MHz as demonstrated in their YouTube video which was watched over 220k times [9]. The design was possibly the first saline water tested in a practical scenario and could be used on space limited navy vessels. It has certainly inspired a lot of interesting research in water-based antennas. Major progresses were made in bandwidth enhancement [50], [51], reconfigurability exploration [52]–[56] and radiation efficiency improvement [14], [57]–[59].

FIGURE 6. **A sea/saline water antenna demonstrated in a video in 2009 [9].**

(a)



(b)

FIGURE 7. **(a) Prototype of a saline water monopole antenna and liquid samples. (b) Calculated radiation efficiency vs conductivity of the saline water monopole antenna at 2 GHz [12], [32].**

A common concern on saline water antennas is the low efficiency which is resulted from the liquid loss tangent or conductivity. A detailed experimental and numerical study on this issue has been reported in [12], [32] where an optimized monopole antenna as presented in Fig. 7(a) was employed. The calculated radiation efficiency as a function of the conductivity of the liquid was obtained at 2 GHz and shown in Fig. 7(b) which was partially validated by measurements. It is interesting to note that the radiation efficiency is over 80% when the conductivity is below 0.001 (the antenna works as a good DRA) or above 1000 (the antenna works as a good

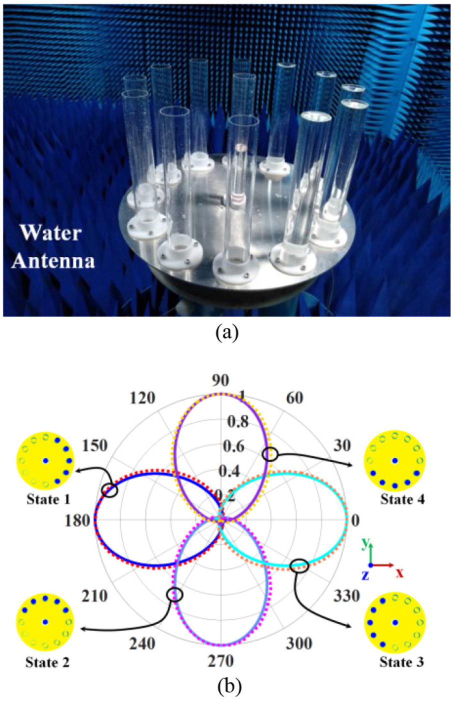


FIGURE 8. **(a) Prototype of a beam-steering saline water antenna; (b) Simulated and measured directional radiation patterns in the azimuth plane at 433 MHz with different working states: State 1 - State 4 [54].**

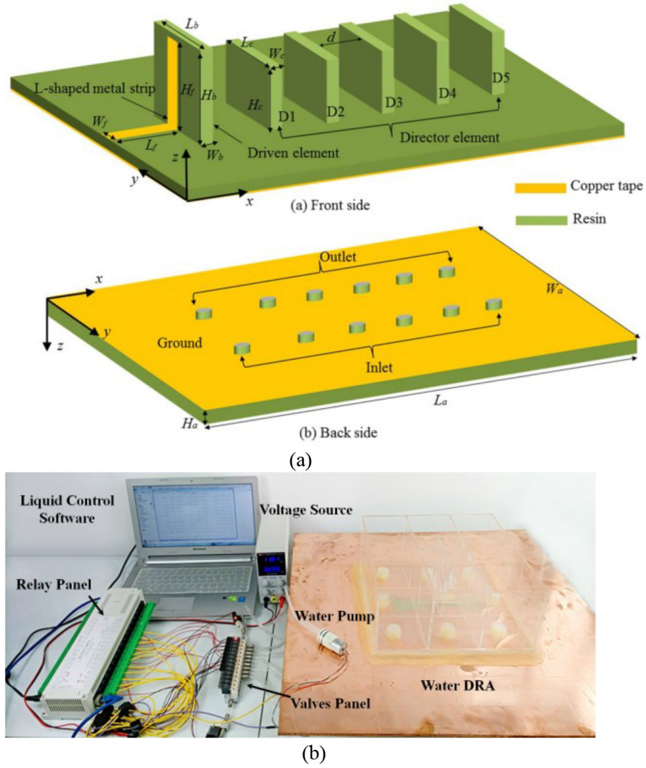


FIGURE 9. **(a) A frequency and beamwidth tunable water antenna [60]; (b) water DRA with an auto-control system [62].**

conducting antenna). The efficiency is lower between these two cases. Seawater has a conductivity of about 3 S/m and its radiation efficiency is therefore below 80%, around 70% in this design which is still reasonable for many applications. The worst case for this monopole is when the conductivity is around 0.1, its efficiency is dropped down to 30%. This reveals that the water-based antenna can achieve high efficiency by properly selecting the right salt concentration and antenna design.

The frequency tuning for such an antenna can be continuous over a wide range. It can also offer at least another advantage: the frequency bandwidth could be changed by not only the diameter of the monopole but also the dielectric layer between the ground plane and the monopole. A demonstration example was given in [51] where a saline water antenna achieved a fractional bandwidth > 70% for $S_{11} < -10$ dB while its equivalent metal antenna has only got a bandwidth less than 20%.

In addition to the frequency reconfigurability, other reconfigurabilities of saline water antennas have also been studied. For example, parasitic monopoles around the driven monopole are implemented to realize pattern reconfiguration [54], [55]. As shown in Fig. 8, when only the driven monopole is excited, the antenna has an omnidirectional radiation pattern; when the driven and selected parasitic monopoles are in use, the water-filled parasitic monopoles would work as reflectors. By configuring the adjacent parasitic monopoles as reflectors or directors, a directive pattern towards a desired direction can be generated [54].

A main problem of most saline water antennas is that their radiation efficiency is low due to the saline water conductivity of around 0.01 - 10 which is lossy as shown in Fig. 7(b). Various techniques have been reported to improve the radiation efficiency of saline water antennas by such as adding a circular disk at the top of feeding probe [57], using a conducting tube and shunt-excited feeding arm [14], employing cylindrical metal rods surrounding the feeding probe [58], and utilizing short metal tube at the base of the water holder [59]. The main idea of these designs is to add metallic element to the antenna to improve the radiation efficiency of the saline water antenna accordingly.

B. PURE WATER ANTENNAS

Compared with saline water, pure water has a lower conductivity (a higher radiation efficiency in this case) and larger permittivity (hence a smaller antenna). It has therefore been used to make a DRA or a hybrid (with metal) antenna. As expected, more pure water antennas have been developed than saline water antennas over the years although they offer the same benefits in terms of the flexibility, reconfigurability, conformability, *et al.*

Various water antennas can be found in the literature: a frequency and beamwidth tunable water antenna was reported [60] and shown in Fig. 9(a) where an L-shaped metallic strip is adopted as the feeding structure of the antenna in order to effectively broaden the operating bandwidth. The L-shaped strip feeder and a rectangular water

(a) (b)

FIGURE 10. Water patch antennas. (a) The water patch antenna integrated with solar cells [15]; (b) An optically transparent water patch antenna [69].

dielectric resonator constitute the driven element. Five identical rectangular water dielectric elements act as directors to control the beamwidth. By varying the height of the liquid water level in the driven element, the antenna is tuned to the desired operational frequency and beamwidth. Polarization switchable water DRAs have also been developed. One example was given in [61]. Most of these reconfigurable water antennas are preconfigured or tuned manually. To overcome this problem, a frequency reconfigurable water DRA with an auto-control system was proposed in [62] and shown in Fig. 9(b). It achieved a high total efficiency (> 80%) across a wide frequency range (from 168 to 474 MHz for $S_{11} < -10$ dB). Various tuning states with diverse combinations of water blocks and water heights were realized in the structure. The developed liquid control system managed the water in a desired way and greatly improved the frequency tuning efficiently. Another challenge associated with water DRA is the possible low efficiency or narrow bandwidth, especially at higher frequencies. To overcome these limitations, a hybrid antenna can be produced by combining a DRA and a metal antenna of two different but close resonant frequencies into one antenna structure so as to broaden the combined bandwidth and increase the radiation efficiency. Two hybrid antenna examples can be found in [19], [63]. Other selected interesting design examples include a water loaded leaky-wave antenna with reconfigurable radiation patterns [64], a frequency reconfigurable metal dipole antenna with bow-tie shaped water loading [65], a pattern reconfigurable monopole antenna with arc-shape water grating [66], and a compact water loaded frequency reconfigurable monopole antenna for DVB-H (digital video broadcasting) applications [67].

Pure water as transparent loading material has great potentials in wearable and Internet of Things (IoT) applications. Its flexibility and unobtrusiveness can enhance users' comfort. An example can be found in [68], where an optically transparent wearable antenna using pure water and conductive mesh was proposed. The pure water worked as a reflector to transform the bidirectional radiation pattern of the antenna to a unidirectional broadside pattern. The antenna achieved a radiation efficiency of 51% at 2.45 GHz and produced a low specific absorption rate (SAR).

Apart from using water as a resonator or dielectric loading, pure water can also act as a reflector. The idea originated from the dense dielectric patch antenna and applied in water patch antenna designs as shown in Fig. 10(a) where an L-shaped probe fed rectangular water patch antenna was introduced. It has a similar working principle as the metal patch antenna. Due to the transparency of water, the antenna was well integrated with solar cells [15]. Further modifications based on water patch structures were produced and presented [69], as shown in Fig. 10(b), both the patch and the ground plane are transparent. A circularly polarized water patch antenna with two diagonal truncated square water patches was given in [70].

In addition to saline water and pure water, an aqueous potassium chloride (KCl) solution is another water-based liquid reported in the literature. In [71], a fluid switch using a KCl solution was employed in a frequency-agile Vivaldi antenna. Two operating frequency bands were achieved by using different back-slot lengths. When the conductive fluid was pumped in the switch, the back-slot presented a shorter effective length and produced a higher operating frequency band. To operate in the lower band, the fluid was drained from the switch, allowing the electric surface current to use the full length of the back-slot. The fluid switch improves the isolation of the two bands and avoids biasing line disturbances. More recently, the authors of [72] and [73] proposed a new fluid antenna system (FAS) where a position-flexible antenna can switch its location freely within a given space. It was demonstrated that even with a tiny space, a single-antenna FAS can outperform a multiple-antenna maximum ratio combining system in terms of outage probability if the number of locations (or ports) the fluid antenna can be switched to is large enough.

Table 4 compares some selected water antennas reviewed in this section. We have tried to make a wide selection of different types of antennas to provide a good coverage of the state-of-the-art of this technology. It can be seen that various water antennas have been developed with their special features and limitations. Most of them have a broad bandwidth and decent radiation efficiency at lower frequencies with advantages in size reduction and low-cost. Most of them can provide discrete or continuous frequency tuning, and reconfiguration in terms of the radiation pattern and/or polarization. However, there are practical concerns on loss, frequency and temperature changes. The knowledge gained from the water-based liquid antenna studies could be a valuable reference for non-water-based liquid antenna and future liquid antenna designs.

VI. NON-WATER-BASED LIQUID ANTENNAS

As discussed in Section III, although anti-freeze could be used to extend the liquid range of water in terms of the freezing point, the EM properties of these water-based materials are too sensitive to temperature and frequency changes for some applications. In such scenarios, water-based antenna may experience large frequency shift or resonant mode variation which results in the reduction of

TABLE 4. Performance comparison of different types of water-based liquid antennas.

Ref.	Antenna Type	Liquid Type	Frequency Range (MHz)	Dimensions (mm^3)	Reconfiguration Type	Tuning Type	Radiation Efficiency (%)
[54]	Conducting antenna	Saline water	334 - 488	300×300×130 ($0.33\lambda_0 \times 0.33\lambda_0 \times 0.15\lambda_0$)	Pattern	Discrete	60 - 82
[55]	Conducting antenna	Saline water	640 - 1470	350×350×178 ($0.75\lambda_0 \times 0.75\lambda_0 \times 0.38\lambda_0$)	Frequency & Pattern	Discrete	38 - 69
[57]	Conducting antenna	Saline water	40 - 200	1000 ($0.13\lambda_0$ antenna height)	Frequency	Continuous	50.2 - 72.3
[58]	Conducting antenna	Saline water	448 - 905	60×60×147 ($0.09\lambda_0 \times 0.09\lambda_0 \times 0.22\lambda_0$)	Static	-	82 - 90
[17]	Water DRA	Pure water	155 - 400	350 × 350 × 150 ($0.18\lambda_0 \times 0.18\lambda_0 \times 0.078\lambda_0$)	Frequency	Continuous	90 - 95
[60]	Water DRA	Pure water	4660 - 5650	50 × 30 × 12 ($0.78\lambda_0 \times 0.468\lambda_0 \times 0.19\lambda_0$)	Frequency & Beamwidth	Continuous	N/A
[62]	Water DRA	Pure water	168 - 474	278 × 278 × 131 ($0.156\lambda_0 \times 0.156\lambda_0 \times 0.073\lambda_0$)	Frequency	Continuous	80 - 94.4
[63]	Hybrid water antenna	Pure water	410 - 870	52 × 51.5 × 10 ($0.077\lambda_0 \times 0.07\lambda_0 \times 0.014\lambda_0$)	Static	-	60 - 80
[64]	Water loaded antenna	Pure water	4100 - 6600	440 × 134 × 12.7 ($6\lambda_0 \times 1.83\lambda_0 \times 0.17\lambda_0$)	Pattern	Continuous	N/A
[68]	Water loaded antenna	Pure water	2370-2540	56 × 56 × 14.5 ($0.44\lambda_0 \times 0.44\lambda_0 \times 0.115\lambda_0$)	Static	-	48-51
[71]	Hybrid fluid antenna	KCI solution	2500-6000	250 × 150 × 1.5 ($2.1\lambda_0 \times 1.25\lambda_0 \times 0.0125\lambda_0$)	Frequency	Discrete	87
[69]	Water patch antenna	Pure water	2000-2850	299 × 299 × 37.6 ($2\lambda_0 \times 2\lambda_0 \times 0.25\lambda_0$)	Static	-	57 - 82

λ_0 refers to the wavelength at the lowest working frequency in the band.

the tolerance and reliability of a radio system. Thus, non-water-based liquid materials have recently been developed and used for making liquid antennas. These antennas use typically either solvent and oil or ionic liquids.

A. LIQUID ANTENNAS USING SOLVENT AND OIL

In this group, ethyl acetate has been used to develop liquid DRAs with the combination of glass housing material to achieve reconfigurability. References [74] and [75] are two examples realized reconfigurable pattern and polarization respectively by pumping the liquid into or out of two different parts of the antenna to produce different modes/polarisations, as shown in Fig. 11. Over 80% radiation efficiency is obtained in the frequency range of 3.5 to 4.5 GHz. Although ethyl acetate seems to have lower loss and wider liquid range compared with water, it is a type of solvent, which means that it may not be chemically compatible with most plastic materials. For example, the 3D-printed container and liquid pipes might be dissolved after a certain period of time when having ethyl acetate inside of them.

Alternative stable and low-loss liquid materials could be transformation oil and Castor oil, which are more chemically stable than solvent. However, the relative permittivity of oil materials is very low, ranging typically from 2 to 3. The antenna size could be relatively large if such oils are employed for making the DRA. They have been utilized as antenna tuning and dielectric loading materials to realize liquid-assisted antenna. Two examples can be found in [76], [77], where the oil was pumped into a cavity underneath the typical metal antenna radiators (e.g., patch), as shown in Fig. 12: by manipulating the volume of loading oil, the antenna frequency could be tuned. The patch example has achieved a wide tunable impedance bandwidth of 32% from 1.42 to 1.96 GHz, which is much wider than that of a conventional microstrip patch antenna. Whilst the radiation efficiency across the realized frequency band is very high ($> 85\%$), demonstrating that such dielectric oil-based materials can be an effective solution for making liquid-assisted (or hybrid) reconfigurable antennas.

B. IONIC LIQUID ANTENNAS

There have been some ionic liquid antennas reported in the literature. In [78], choline L-alanine was, for the first time, used to develop a wideband circularly polarized (CP) liquid DRA shown in Fig. 13(a). The feeding structure is of a special spiral shape; thus, the antenna would be really hard to

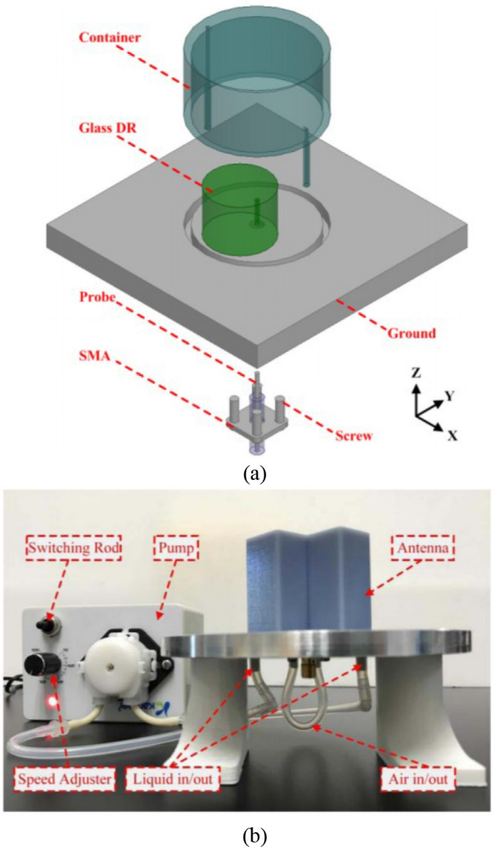


FIGURE 11. (a) Pattern reconfigurable DRA [74] with/without the liquid filled between the container and glass DR; (b) Two-zone CP polarization reconfigurable liquid DRA using ethyl acetate [75].

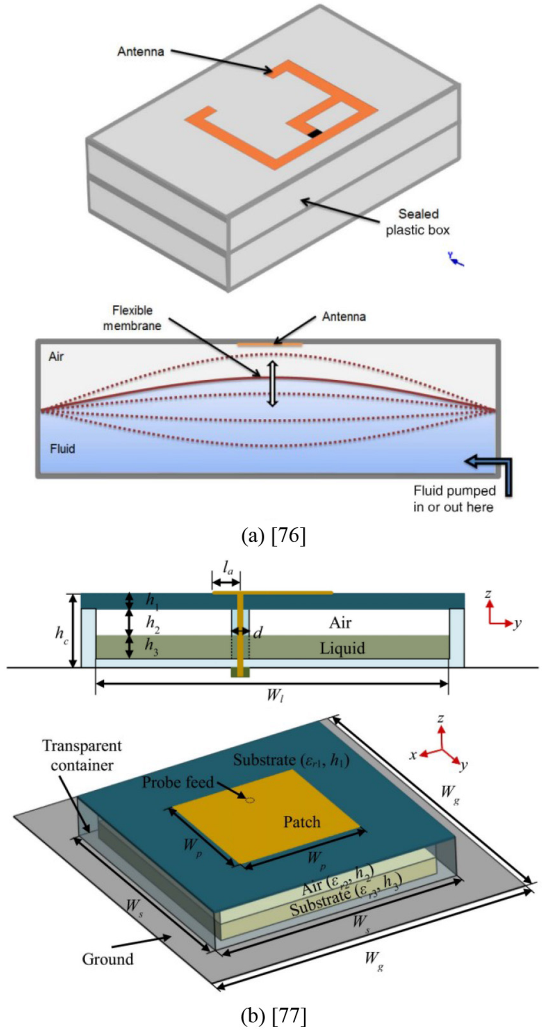


FIGURE 12. Two frequency tunable antennas using liquid oil as loading materials.

realize if the antenna were made of a solid dielectric material. The liquid range of this liquid compound is from −56 °C to 186 °C, its electrical conductivity is about 0.00021 S/m. Furthermore, it is non-toxic, nonflammable and does not evaporate. The antenna has realized 34% CP bandwidth (from 1.5 to 2.1 GHz) and over 80% total efficiency across the frequency band of interest. The antenna performance is comparable to typical DRAs, but its overall size is reduced to $0.43 \times 0.43 \times 0.09\lambda_0^3$. This example has demonstrated the advantage of using an ionic liquid material.

Another low-loss ionic liquid material, T-chloride, was used as a new type of dielectric antenna loading material (with relative permittivity = 3.2) in [79]. The conductivity of this liquid is around 0.00025 S/m, while its loss tangent is smaller than 0.001 at operational frequency. Moreover, it is a colorless liquid with a relatively low density of 0.895 g/mL at room temperature. Several monopole antennas in this paper have shown that the antenna size could be reduced by 40% when using such an ionic liquid loading, while the total efficiency over a very wide frequency band is greater than 85%. A hybrid antenna of a DRA and a magnetoelectric dipole (ME dipole) was proposed in [80] and shown in Fig. 13(b). Taking advantage of the liquid dielectrics, the ME dipole was fully immersed into the ionic liquid to reduce the size and especially the height, at the same time it produced multiple resonant modes and resulted in an extremely wide combined bandwidth (73.5%). This design has achieved an efficient > 80% over the desired frequency band, and the electrical size of the radiator is less than 0.4 λ_0, showing that such ionic liquids can be indeed used to develop excellent liquid antennas or hybrid antennas.

In addition to the well-known reconfigurability of a liquid antenna in frequency, radiation pattern and polarization as already mentioned, a very special design utilizing two liquids of different permittivities has achieved passive beam steering due to the fluidity and gravity of the liquid, without using electrical or mechanical steering system [23]. The antenna is presented in Fig. 14(a) and its radiation patterns for 5 different antenna positions are passively steered upwards as shown in Fig. 14(b). It could be used for applications such as satellite communications or GPS where a stable beam towards the sky is required. The two low-loss liquids are: perfluorodecalin with a relative permittivity of about 2.1 and acetone mixtures with acetone oxime with a relative permittivity of about 13. The selection of the materials is very important since they can maintain independence within the

TABLE 5. Performance comparison of different liquid antennas and solid traditional antennas.

Comparison specs	Metallic liquid antennas	Water-based liquid antennas	Non-water-based liquid antennas	Traditional antennas
a) Antenna efficiency	High efficiency (> 80%)	Frequency and temp. dependent, typically around 50%	High efficiency (> 80%)	High efficiency (> 80%)
b) Performance stability against temperature	Very stable but limited temp. range	Not stable and limited temp. range	Stable over a large temp. range	Very stable over a large temp. range
c) Reconfigurability	Good	Very good	Very good	Limited
d) Design flexibility	Good	Limited	Limited	Very good
e) Fabrication	Medium	Hard	Hard	Easy
f) Safety	Material dependent	Safe	Not safe for oils and solvents but safe for ionic liquids	Very safe

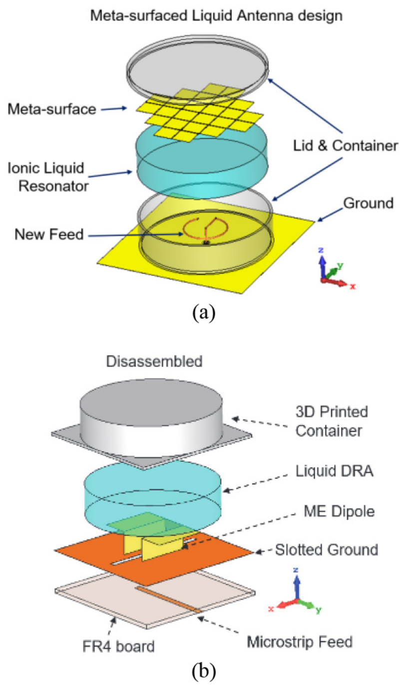


FIGURE 13. Two ionic liquid antenna examples. (a) Broadband CP liquid antenna [78]. (b) Hybrid liquid DRA and ME dipole antenna [80].

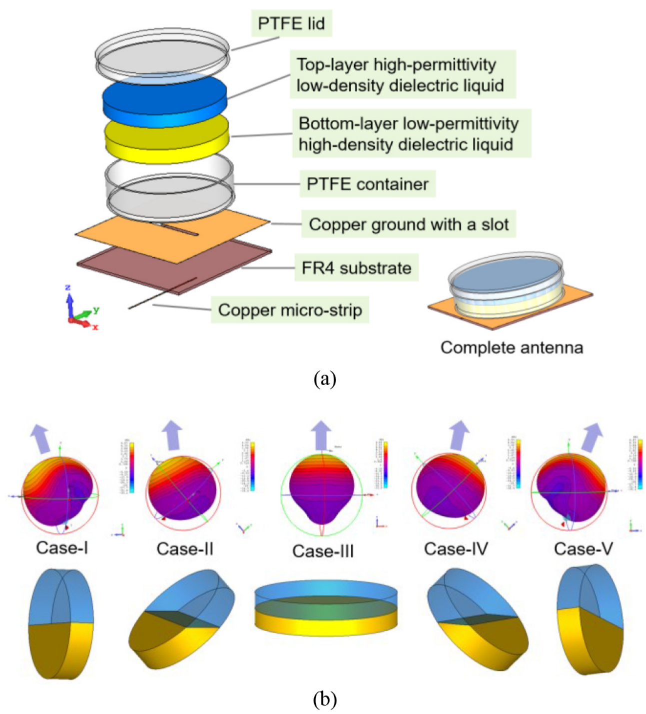


FIGURE 14. A passive beam-steering liquid antenna. (a) The structure of the antenna. (b) Radiation patterns for five different antenna positions [23].

same container without chemical reaction and immiscible or resolvable with each other.

VII. DISCUSSION AND CONCLUSION

We have now discussed all types of liquid antennas and their associated materials. A performance comparison table of the metallic liquid antennas, water-based antennas, non-water-based liquid antennas, and traditional metal antennas is provided in Table 5 where both water-based antennas and non-water-based liquid antennas are assumed to be dielectric antennas since they work best in this mode (although they can act as conductive antennas whose loss is high in general). They are compared in terms of the following parameters:

a) *Antenna efficiency:* Most of them can achieve high efficiency. For water-based antennas, the efficiency is normally not high, but it depends on the operational frequency, the water "quality", and the antenna design. At lower frequencies (below 1GHz), the dielectric loss of pure water can be small, thus the antenna efficiency can be relatively high as shown in Table 4. It should be pointed out that the antenna efficiency is also affected by the housing material, not just the liquid.

b) *Performance stability against temperature:* Overall, traditional antennas outperform liquid antennas. For metallic liquids, as we have seen in Table 1, the metallic liquid is sensitive to temperature, even the best one (Galinstan) has a limited liquid range (from −19 °C). Water-based liquid antennas have the worst performance, their freezing/melting point is high, and the EM properties are sensitive to the frequency and temperature change. However, non-water-based, especially ionic liquid antennas have shown very good and stable performance over a very large temperature and frequency range.

c) *Reconfigurability methods:* Liquid antennas have more options than traditional antennas. In addition to electrical reconfigurable method (normally based on switch or varactor), they can also be reconfigured through mechanical (e.g., liquid pumps) and even gravitational methods using the fluidic feature. Furthermore, chemical and thermal methods (not suitable for metallic liquid antennas) are also possible but good designs are not available yet.

d) *Design flexibility:* This could include a lot of things. Here we mean the flexibility by changing the antenna physical configuration (such as the size, shape, and feeding) to meet the design specifications. The conventional metal antenna is the best, the metallic liquid antenna comes second, and the non-metallic liquid antenna is the worst in this regard. The main reason is that, unlike a metallic antenna, a dielectric liquid antenna (like a solid DRA) performs well only when a resonant mode is excited at the desired frequency which has placed certain restrictions on the physical dimensions and feeding method of the antenna. For example, we cannot make a very thin or electrically small dielectric liquid antenna to work well, but we can do it using conductive materials. This is a main drawback of non-conductive liquid antennas. On the other hand, liquid can be used to form a hybrid antenna which offers a flexibility not available in traditional antennas.

e) *Fabrication:* Unlike a conventional solid antenna, the liquid in most liquid antennas has to be guided or contained in a holder. The whole system should be sealed to avoid leakage. Thus, the fabrication process or packaging of a liquid antenna is more complicated than that of the traditional antenna. The metallic liquid antenna is ranked higher than the non-metallic liquid antenna, because some metallic liquid antennas could be fabricated using printing technology and no holder is required.

f) *Safety:* This is an important issue and could refer to safety for human being as well as for environment in different scenarios, including such as high-power operation, harsh environment, aging, *et al.* The traditional antennas are well established and are made very safe while for liquid antennas, they are relatively new and to be further investigated and tested although water-based materials and ionic liquids are safe to use.

It is apparent that each type of antennas has its own advantages and limitations. A very important and widely asked question is: what are the main advantages that liquid antennas have over the traditional antenna? As we have seen in this review, liquid antennas have demonstrated that they can offer the following main advantages over the traditional antenna:

- Reconfigurability,
- Flexibility and conformability,
- Fluidity,
- Transparency,
- Size reduction.

There are also other possible benefits such as low-cost, eco-friendly and low radar cross section which will depend on the specific design. Another potential advantage is to integrate liquid antenna with the cooling system of the device, resulting in space and energy saving which is an interesting area to be further explored.

In terms of the suitable frequencies, most of the developed liquid antennas are for 2 MHz to 18 GHz. In principle, liquid antennas are suitable for any frequency. But in practice, the frequency range may be limited by issues such as the dielectric loss, especially at higher frequencies. The good news is that some ionic liquids have shown excellent performance at higher frequencies (higher than 18 GHz which was limited by measurement facilities [33]).

Although a considerable amount of progress has been made on the research and development of liquid antennas over the past 20 years, it is a pity that we have not yet seen it implemented in a commercial product. To make it a reality, in addition to finding better and smarter liquid antenna designs, we also need to deal with the following challenges:

1) *How to implement the reconfigurability:* To realize the special reconfigurability of a liquid antenna, the current mechanical pumping method may be acceptable for some applications, but it is not convenient/practical enough for most, as the system is not small, and the slow tuning speed could also be an issue for practical use, a better solution is required.
2) *How to make it robust enough:* Ionic liquids seem to be the best choice for dielectric liquid antennas due to their low loss and stable temperature and frequency response. However, all liquid antennas have not been thoroughly tested and evaluated for different environments, dielectric containers, and microwave power levels (power handling capacity is a very important parameter for many applications). The robustness of such antennas is mostly unknown yet.
3) *How to fabricate and package the antenna:* The laboratory prototypes are for research and proof of concept purposes. How to fabricate an industrial standard liquid antenna on a large scale is yet to be developed. Furthermore, problems associated with the packaging and feeding of the antenna are to be resolved.

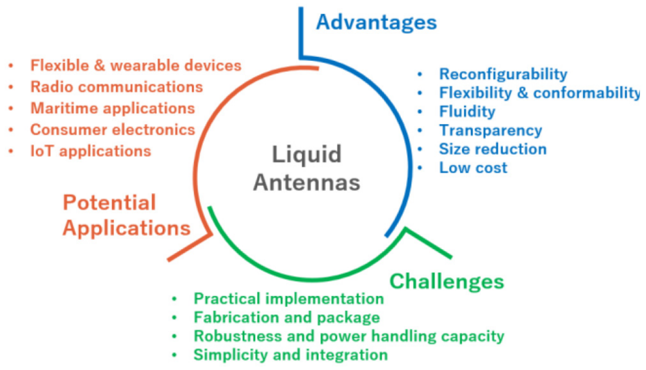


FIGURE 15. Summary of the advantages, challenges, and potential applications of liquid antennas.

4) *How to reduce the complexity and overall size:* Although the size of a liquid antenna may be smaller than the size of its metal antenna counterpart, once we include all the associated feeds, liquid containers, pumping and control system, the overall size of the antenna system may not be small. How to reduce the complexity and produce a well-integrated design are to be addressed.

These challenges could also be considered as the topics for further study and development in the future. We believe that the implementation of liquid antennas for real-world applications may start from hybrid or liquid assisted antennas without considering liquid metal antennas which are very similar to conventional antennas. That is to combine a metal antenna with a liquid antenna, as demonstrated in such as [19], [60], [63], [80]; the hybrid antenna can combine the advantages of both antennas to broaden the bandwidth and reduced the overall size of the antenna. It can also be made reconfigurable as shown in [60], [76], [77]. Another very promising direction is to use some unique features of the liquid antenna, such as fluidity, gravity and/or transparency to realize some special functions which are not available in conventional antennas as demonstrated in [23], [69], [81]. Close collaboration between researchers and industry can also accelerate the innovation of the liquid antenna for real-world applications.

It is clear that the possible applications of liquid antennas are not limited to radio communications (e.g., 5G and beyond) and navigations (e.g., GPS), but also suitable to other areas such as maritime applications, smart vehicles, consumer electronics (e.g., new smart wearables and flexible devices) and IoT applications. From an industrial perspective, this technology is very attractive, and some designs are already very close to meeting product requirements.

The advantages, challenges as well as potential applications of liquid antennas are summarized in Fig. 15.

Finally, a website [82] dedicated to liquid antennas is developed for promoting liquid antenna research and sharing information, data, and resources, with the ultimate goal to develop innovative and smart liquid antennas for real-world applications.

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