Abstract—A novel broadband circularly polarized (CP) antenna using organic ionic liquid resonators is presented in this communication for the first time. The antenna is excited by inserting a new feeding structure into the liquid which is relatively simple but significantly improves the bandwidth and CP performance of traditional single probe-fed dielectric resonator antennas (DRAs). The proposed liquid antenna is loaded with a metasurface (MS) to further improve the impedance matching and CP characteristics. A design example of the proposed antenna shows a relatively wide fractional impedance bandwidth and CP bandwidth of 51.4% and 34.2%, respectively. In addition, the proposed liquid DRA has a reduced structural complexity and a compact size compared with the conventional DRAs with a similar performance. The design methodology presented in this communication can be further exploited for a range of new liquid DRA designs and expand the design freedom and flexibility of such antennas which may have significant implications in future antenna designs using the new liquid materials.

Index Terms—Circular polarization (CP), dielectric resonator antenna (DRA), liquid antennas, metasurface (MS), organic ionic liquid.

I. INTRODUCTION

Wideband circularly polarized (CP) antennas have been widely adopted for many wireless systems such as radio frequency identification (RFID), radar, satellite navigation, and communications [1]–[6]. Such CP antennas are capable of mitigating polarization mismatch and suppressing multipath interference, which could significantly improve the quality of communication in the aforementioned systems.

In recent years, dielectric resonator antennas (DRAs) have become increasingly popular and identified as suitable candidates for developing wideband CP antennas [7]–[12]. Traditional DRAs are typically made using solid materials (e.g., low-loss glass and ceramic). Thus, the excitation of the CP radiation for such DRAs is mainly achieved by means of cutting the dielectric resonator (DR) shapes [7], [13], [14] and/or introducing additional feeding networks [15]–[18]. As a consequence, the cost and manufacturing complexity of these conventional CP DRAs are relatively high. In addition, the solid material-based DRAs typically have limited capability to accommodate special feeding structures, especially when the antenna feed is inserted into the DRA. Therefore, these antennas generally have restricted design freedom and performance.

II. LOW-LOSS ORGANIC IONIC LIQUIDS

Liquid antennas have attracted increased research interest due to their advantages in realizing small, transparent, reconfigurable, and flexible antennas for emerging and future applications [19]. Water-based DRAs have been successfully demonstrated in laboratories with limited real-world applications [20]–[24]. The main drawbacks of water may include the relatively high dielectric loss at higher frequencies, temperature-dependent performance, and phase changes such as turning to ice if the temperature goes below 0 °C. To address these drawbacks, some dielectric solvents have been selected for use in place of water, due to their much smaller loss tangent (LT), stable dielectric relaxation, and lower freezing point [25]. However, such solvent-based liquid antennas still have problems. For example, most organic solvents are flammable and with high vapor pressures, resulting in high evaporation rates and potential safety concerns.

To overcome the aforementioned challenges, here we present a novel broadband CP antenna design using new ionic liquid materials with attractive material properties. Moreover, a novel yet simple feeding structure consisting of a single metal probe is introduced to excite a wideband CP radiation for the liquid antenna. A metasurface (MS) is utilized in the proposed design to further improve the CP characteristics and device performance. The proposed liquid antenna has shown a greatly improved wideband CP performance with much-reduced complexity compared with traditional designs. This work also offers a new idea and a new material to build liquid DRAs using an inserted feed with a simple structure.

The rest of this communication is organized as follows. A new ionic liquid is introduced in Section II. The development of the new feeding structure is presented in Section III. The addition of an MS and experimental validations are discussed in Sections IV and V. Finally, conclusions are drawn in Section VI.
feeding methods in the traditional DRA systems. An example of a

A. Traditional Single Probe Center-Fed DRA

an ionic liquid 1-butyl-3-methylimidazolium tetrafluoroborate
(C4MIM BF4) has a very low freezing point down to −70 °C and
an extremely high boiling point of 430 °C. However, the electrical
conductivity $\sigma$ of 1-butyl-3-methylimidazolium tetrafluoroborate is
around 0.352 S/m, resulting in a relatively high LT for frequencies
over 1 GHz. Thus, a completely organic ionic liquid (choline
L-alanine) easily prepared from readily available starting materials is
proposed here with a significantly lower LT. The liquid range of this
compound is −56 °C–186 °C, while its electrical conductivity is as
low as 0.00021 S/m [27]. Notably, such ionic liquids have no safety
concerns and are typically environmental friendly. The broadband
dielectric spectroscopy of choline L-alanine was measured by using a
Keysight dielectric slim probe. The photograph of the measurement
setup is shown in Fig. 1. The measured relative permittivity (the
real part of the complex permittivity) and LT of choline L-alanine
are shown in Fig. 2 over the frequency band of 0.5–5 GHz. As can
be seen from Fig. 2, the relative permittivity of choline L-alanine is
around 12–8 over the band, while the LT is relatively small, ranging
from 0.02 to 0.1 across the band. This shows that the choline
L-alanine is a suitable material for making liquid DRAs due to
its low loss, low electrical conductivity, and stable thermophysical
properties.

III. NOVEL FEEDING SCHEMES FOR THE LIQUID ANTENNA

A. Traditional Single Probe Center-Fed DRA

The center-fed single probe scheme is one of the most popular
feeding methods in the traditional DRA systems. An example of a
cylinder liquid DRA fed by using a single straight probe is depicted in
Fig. 3. The ground plane here is typically a metal sheet being
electrically connected to the outer conductor of an SMA connector.
The feeding probe is inserted into the liquid DR from its bottom
center and is electrically connected to the inner conductor of the

Fig. 1. Setup for the proposed organic ionic liquid measurements. A Keysight
dielectric slim probe was used [30].

Fig. 2. Measured relative permittivity and LT of the proposed ionic liquid
choline L-alanine.

SMA. In this case, the $TM_{015}$ mode of such cylinder DRAs could
be excited [28].

The detailed notations of the antenna parameters are shown in
Fig. 3. Here, we select $W_D = 80$ mm, $H_D = 19$ mm, $H_P = 10$
mm, $H_L = 4$ mm, and $G = 100$ mm as a design example. The overall
dimension of the antenna is $100 \times 100 \times 21$ mm$^3$. According to
the design formulas of the cylinder DRA [28], the resonant frequency
at the mode $TM_{015}$ of this antenna using the proposed ionic liquid
resonator (choline L-alanine) can be calculated using

$$k_0r = \sqrt{\frac{3.83^2 + (\pi x/2)^2}{\sqrt{\sigma_r + 2}}}$$

(1)

$$k_0r = \frac{f_{GHz} \cdot h \cdot \epsilon_r}{4.7713}$$

(2)

where $x = r h$, $r$ is the radius of the DR ($r = 0.5 \times W_D = 40$ mm),
h is the height of the DR ($h = H_P = 19$ mm), $h_{cm}$ is the value (without
units) of $h$ in centimeters, and $\epsilon_r$ is the relative permittivity of the
DR. As a result, the estimated resonant frequency ($f_{GHz}$) of $TM_{015}$
mode of the proposed liquid DRA is around 2.1 GHz. Fig. 4 shows
the simulated E-field distribution (2-D cut in the XOZ plane) and 3-D
radiation pattern of the DRA at 2.1 GHz. It is noted that the E-field
in this case is similar to that of a quarter-wavelength monopole being
placed over a ground plane. The E-field is “sprayed” from the feed
point and equally distributed on both sides of the probe [see arrow
markers shown in Fig. 4(a)]. Such an E-field distribution leads to
an omnidirectional radiation field with a maximum gain of 1.86 dBi
and a radiation null at the antenna boresight direction. The simulated
reflection coefficient of the aforementioned liquid DRA is shown in
Fig. 5(a). It can be seen that the antenna covers a band of 2–2.2
GHz with a center frequency at 2.1 GHz, which verifies the theoretical
prediction. It is concluded that the traditional single probe center-fed
DRA has a limited bandwidth, low gain, and omnidirectional radiation
pattern when the feeding probe is located at the bottom center.

B. Modified Feeding Scheme for the Liquid DRA

To improve the performance of the aforementioned liquid DRA,
here we introduce a new feeding structure which is a combination
of the traditional single probe and an extra vacant-ring structure,
as shown in Fig. 6. In this scenario, the electromagnetic field
distribution of the new antenna is changed. The notations of the main
parameters of the vacant ring are shown in Fig. 6(b). In this example,
we use $R_L = 14$ mm, $W_L = 1$ mm, and $D_L = 11$ mm. The antenna
is simulated using the CST MWS software. The simulated reflection

Fig. 3. Traditional single probe-fed cylinder liquid DRA and its $TM_{015}$
mode. The detailed dimensions of the antenna are given in Section III-A.

Fig. 4. Simulated (a) E-field distribution and (b) 3-D radiation pattern at
2.1 GHz of the cylinder liquid DRA using a single probe-fed scheme.
To better understand how this new antenna works, we have first calculated the reflection coefficient of the antenna without loading the liquid. As shown in Fig. 5(b), there are four troughs around 2.4, 3.8, 5.2, and 7.5 GHz. The corresponding radiation patterns at these four frequencies are given as well. It can be seen that the antenna has a broadside radiation pattern at 3.8 GHz, while the pattern is tilted to other directions at 2.4, 5.2, and 7.5 GHz. Once the antenna is loaded with the liquid material, we can see from Fig. 5(a) that there are troughs around 1.4, 1.7, 2.3, and 2.5 GHz in its $S_{11}$ which do not seem to be the result of simply scaling the four troughs by a factor of $\sqrt{r}$ (about 3 in this case). The dielectric resonance in the antenna may have contributed to these troughs. We have then calculated the resonant frequency and quality factor ($Q$-factor) of the cylindrical liquid DRA under the $HEM_{115}$ mode (the first mode for the excitation) using the equations as follows [28]:

$$k_0r = \frac{6.324}{\sqrt{r} + 2} \left[0.27 + 0.36(x/2) - 0.02(x/2)^2\right]$$  \hspace{1cm} (3)

$$Q = \frac{1}{0.1007\varepsilon_{r}^{-1.3}} \left[1 + 100e^{-2.05(x/2-x^2/80)}\right].$$  \hspace{1cm} (4)

The calculated $HEM_{115}$ mode resonant frequency is around 1.6 GHz and the calculated $Q$-factor is about 5. Therefore, the frequency bandwidth is approximately 1.6 GHz/$Q = 0.32$ GHz. Thus, the major trough in $S_{11}$ between 1.6 and 2.0 GHz is due to the $HEM_{115}$ mode and effect of the feeding structure. Unidirectional broadside radiation patterns are realized over the aforementioned band. We can also show that the resonant frequency for $HEM_{123}$ mode is around 2.6 GHz, which is another trough observed in Fig. 5(a). Therefore, the wideband and multiband performance is likely due to the combination of the DR resonances and the wideband curl-like feed. In addition, this new feeding structure is similar to the curl antenna [31], which has realized a wideband CP radiation of the antenna.

It is worth noting that the proposed new feeding structure would be hard to realize in the conventional solid material-based DRA systems, since it would be costly and impractical to drill a special hole in solid materials (e.g., glass and ceramic) to accommodate such a vacant-ring structure. However, it is easy for the liquid DRA antenna to accommodate the proposed special feeding scheme. This is a unique advantage of the proposed liquid antenna.

IV. METASURFACE LOADING FOR IMPROVING THE CIRCULARLY POLARIZED RADIATION

The proposed new antenna can generate a CP radiation field due to the introduction of the vacant ring. However, having conducted an in-depth optimization for the ring, we found that the frequency bandwidth for the CP radiation is limited. The state-of-the-art technology showed that the utilization of MSs could improve the CP performance for a range of typical metal/PCB antennas [29]. However, the feasibility of using the MS in DRA and liquid antenna designs has not been demonstrated before. The study here is to see if the CP characteristics of the liquid antenna could be improved by adding an MS.

The MS is normally defined as a periodic array of scattering elements with subwavelength periodicity. The structure of the MS liquid antenna is depicted in Fig. 8. It can be seen that the proposed MS consists of an array of periodic square patches and is pasted onto the lid (inner surface) of the antenna. Square patch-based MSs (SPMSs) could offer an excellent polarization independence and meanwhile generate additional resonances via the means of surface wave propagation. When the driven element underneath the SPMS is CP, the surface wave resonance could be CP as well, thus
The dispersion diagram of the SPMS at the first two eigenmodes is the number of unit cells, and $P$ is the periodicity of the MS. The feed probe (driven element) is underneath the SPMS, the dispersion diagram of surface waves within the SPMS is also important. The size of a single MS unit cell is $W_S \times W_S = 12 \times 12 \text{ mm}^2$ with a metal patch thickness of 0.1 mm, while the gap between the cells is $G_S = 0.4 \text{ mm}$. The electrical size of the unit cell at 1.57 GHz is only 0.06$\lambda_0 \times 0.06\lambda_0 \times 0.0005\lambda_0$. The simulated reflection phase diagram of the proposed MS is shown in Fig. 9(a). It can be seen that the perfect magnetic conductor (PMC) bandwidth ($\approx 90^\circ < \beta < +90^\circ$) has covered 1.4–2.2 and 2.5–3 GHz which have a good overlap with our impedance frequency bands shown in Fig. 5(a). Since the feed probe (driven element) is underneath the SPMS, the dispersion diagram of surface waves within the SPMS is also important. The frequency of the surface wave resonance can be determined by [29]

$$\beta_{SW} \times P = \pi / N \quad (5)$$

where $\beta_{SW}$ is the propagation constant of the surface wave, $N$ is the number of unit cells, and $P$ is the periodicity of the MS. The dispersion diagram of the SPMS at the first two eigenmodes [transverse magnetic (TM) and transverse electric (TE)] are simulated using the eigenmode solver of the CST and presented in Fig. 9(b). When $N = 5$, we have $360/\pi \times \beta_{SW} \times P = 72^\circ$. The calculated resonant frequencies for the TE and TM surface waves are 2 and 2.2 GHz, respectively [see Fig. 9(b)]. Since the proposed SPMS has $4 \times 4$ unit cells with 8 cell extensions (24 cells in total), the surface wave resonances of the MS are roughly at 2–2.2 GHz.

For full antenna simulation, the container and lid were modeled using Perspex acrylic with a relative permittivity of 2.5. The simulated reflection coefficient of the proposed liquid DRA with the SPMS is shown in Fig. 10(a). To make a comparison, the reflection coefficients of the previously discussed two antennas in Sections III-A (single probe feed) and III-B (modified feed) with the same package are shown as well. As can be seen from Fig. 10(a), the addition of the SPMS has improved the impedance matching between 1.3 and 1.6 GHz. The bandwidth of the MS liquid DRA for reflection coefficient $<-10 \text{ dB}$ is from 1.3 to 2.2 GHz with a corresponding fractional bandwidth (FBW) of 51.4%. However, as a comparison, the FBWs of the antennas with a single probe feed and the modified feed are just 10% and 24%, respectively. Moreover, the proposed ionic liquid material has a dielectric relaxation effect over the frequency band of interest [27]. According to Fig. 2, the relative permittivity drops from 10.5 (at 1.25 GHz) to about 8.5 (at 2.25 GHz), which have helped to improve the bandwidth of the proposed antenna. As a comparison, the simulated reflection coefficients of the proposed antennas by using dielectric materials with a fixed permittivity are depicted in Fig. 10(b). It can be seen that the resonant frequency bands for a fixed dielectric constant of 10 and 8 are about 1.26–1.8 and 1.5–2.4 GHz, respectively, in which the antenna using the ionic liquid has achieved a wider bandwidth that roughly combines the aforementioned two bands. It is worth noting that there is a tiny air gap between the MS and the liquid resonator, as shown in Fig. 8(b). The size of this air gap may slightly affect the antenna performance. It was found that the resonant frequency of the antenna goes up by increasing the size of the air gap. Therefore, in this communication, we have minimized the gap size (around 1 mm) to cover the frequency band of interest (GPS L1 band). The simulated E-field distribution and 3-D radiation pattern at 1.57 GHz of the proposed liquid DRA are depicted in Fig. 11. It can be seen that the E-field propagates through the MS in the antenna boresight direction. As a consequence, the antenna realizes a unidirectional radiation pattern with a maximum gain of 6.33 dBi.

To illustrate the improvement in the CP characteristics, the simulated frequency dependence of the axial ratio (AR) of the proposed antennas with/without using the MS is shown in Fig. 12. It can be seen that the minimum point of AR is shifted from 1.85 (no SPMS) to 1.6 GHz (with SPMS) after using the MS. In addition, an extra AR minimum point is observed at 2 GHz. This is due to
V. EXPERIMENTAL VALIDATIONS AND PERFORMANCE COMPARISON

To validate the antenna performance, we have made and tested the proposed antenna prototype (see Fig. 15) based on the optimized dimensions. The cylinder-shaped container and screw-threaded lid were entirely machined from a single rod of Perspex acrylic (\(\varepsilon_r \sim 2.5\)). The feeding probe was made using a single copper wire with a diameter of 1 mm. The antenna was measured by using a Keysight portable VNA (N9917A FieldFox). The measured reflection coefficient and AR are shown in Fig. 14 along with the simulated results for comparison.

In general, good agreement between the experimental and simulation data was obtained. The proposed liquid antenna prototype covered a band from 1.3 to 2.2 GHz, whereas its CP bandwidth (AR < 3 dB) was about 1.5–2.1 GHz. Therefore, the wideband CP performance of the antenna has been verified. In addition, it is noted that the electrical size of the antenna was reasonably compact, around \(0.43\lambda_0 \times 0.43\lambda_0 \times 0.09\lambda_0\) (at 1.3 GHz), which was comparable to other relevant DRA designs. The simulated and measured realized gains (at the antenna broadside direction) and total efficiencies of the antenna are shown in Fig. 15. It can be seen that the antenna had a broadside radiation across 1.3–1.9 GHz, while the realized gain and efficiency were higher than 4 dBi and 80%, respectively, over the frequency band of interest. The main radiation directions at 1.9–2.2 GHz were shifted to other directions due to the higher order resonant mode generation of the DR. Thus, the realized gain at this band dropped from 5 dBi to about \(-2\) dBi in the broadside direction. It should be noted that the introduction of the MS has improved the antenna gain by about 1 dBi over the main band of interest at 1.3–1.9 GHz. Meanwhile, the MS reduced the antenna gain by around 1.5 dBi for the band of 1.9–2.2 GHz. This was due to the increased reflection and scattering loss in this band caused by the utilization of the MS.

Moreover, the 2-D plots of the measured and simulated radiation patterns at 1.57 GHz are depicted in Fig. 16. A unidirectional radiation pattern with a relatively wide half-power beamwidth of 93° has been achieved for the RHCP radiation field. As the presented liquid antenna design example realized a wide impedance bandwidth as well as a wide CP bandwidth covering a range of GPS bands (e.g., 1.57 GHz) with a high-gain unidirectional RHCP radiation,
it could be an excellent candidate for GPS and Global Navigation Satellite System (GNSS) applications.

The performance comparison between the proposed antenna and some related DRAs and some latest CP antennas are given in Table I. Our antenna achieves a relatively wide bandwidth for broadside CP radiation (with a reflection coefficient $<$ -10 dB, AR $<$ 3 dB, and realized gain $>$ 4 dBi at the antenna boresight). Meanwhile, the proposed antenna has a compact size, a relatively simple structure, fabrication process compared with the existing CP DRAs with a good performance. The height of the antenna is about 0.09λ, which is smaller than most wideband DRA designs. The overall dimension of our antenna is comparable with that of the microstrip patch-based MS antennas [29]. Moreover, we have demonstrated the feasibility of our antenna is similar to that of the microstrip patch-based MS antennas [29].

VI. CONCLUSION

In this communication, we have presented a novel broadband CP antenna design using organic ionic liquid resonators. The liquid resonators were made of choline L-alanine with an impressive liquid range from -56 °C to 186 °C, an extremely low loss and a stable material property compared with the existing water- and solvent-based designs. In addition, a simple feeding scheme formed by using a single metal probe has been designed to broaden the bandwidth, improve the gain, and excite the resonant mode of the proposed liquid antenna. The antenna has been incorporated with an MS to improve the CP performance. We have theoretically proved and experimentally verified a liquid antenna prototype that achieved a wide impedance bandwidth of 1.3–2.2 GHz as well as a CP bandwidth of 1.5–2.1 GHz. The prototype has shown a reduced structural complexity and a compact size of 0.43λ × 0.43λ × 0.09λ compared with prior-art designs with a similar performance. It was, therefore, suitable for a range of GNSS and communications applications. The design presented in this communication is just an example to illustrate the proposed antenna concept. The design is quite straightforward and is easy to follow. Therefore, the antenna could be easily scaled for other operating frequencies. The details of the SPMS and feeding structure could be further modified for any other specific applications. Importantly, the presented work has shown a great potential to develop novel liquid antennas using new materials and design techniques, which will attract significant research interest.

TABLE I

<table>
<thead>
<tr>
<th>Ref. (year)</th>
<th>Impedance bandwidth (GHz)</th>
<th>CP bandwidth (GHz)</th>
<th>Electrical and physical size of the complete antenna</th>
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<tr>
<td>[13] (2018)</td>
<td>6.5–7.6 (FBW = 48.3%)</td>
<td>5.47–6.37 (FBW = 15.4%)</td>
<td>0.78λd × 0.78λd × 0.20λd</td>
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<td>[14] (2014)</td>
<td>2.79–3.56 (FBW = 24.3%)</td>
<td>2.92–3.56 (FBW = 19.8%)</td>
<td>1.3λd × 1.3λd × 0.11λd</td>
</tr>
<tr>
<td>[7] (2018)</td>
<td>2.2–3.5 (FBW = 44.8%)</td>
<td>2.19–3.53 (FBW = 46.9%)</td>
<td>0.55λd × 0.55λd × 0.14λd</td>
</tr>
<tr>
<td>[15] (2018)</td>
<td>2.1–2.96 (FBW = 34%)</td>
<td>2.32–2.96 (FBW = 24.2%)</td>
<td>0.69λd × 0.69λd × 0.27λd</td>
</tr>
<tr>
<td>[25] (2018)</td>
<td>2.08–2.98 (FBW = 35.6%)</td>
<td>2.31–2.73 (FBW = 16.3%)</td>
<td>0.42λd × 0.42λd × 0.23λd</td>
</tr>
<tr>
<td>[29] (2015)</td>
<td>4.7–7.48 (FBW = 45.6%)</td>
<td>4.9–6.2 (FBW = 25.4%)</td>
<td>0.52λd × 0.54λd × 0.06λd</td>
</tr>
<tr>
<td>This work (2019)</td>
<td>1.3–1.9* (FBW = 37.5%*)</td>
<td>1.5–1.9* (FBW = 23.5%*)</td>
<td>0.43λd × 0.43λd × 0.09λd</td>
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</tbody>
</table>

*This represents the bandwidth for the broadside radiation with a reflection coefficient $<$ -10 dB, AR $<$ 3 dB, and realized gain > 4 dBi at the antenna boresight.

TABLE II

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<th>Table II</th>
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<td>COMPARISON OF THE PROPOSED LIQUID ANTENNA AND RELATED DESIGNS</td>
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REFERENCES


