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A Polarization-Reconfigurable Wideband High-Gain Antenna Using Liquid Metal Tuning

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Abstract—This paper presents a polarization-reconfigurable wideband high-gain antenna based on liquid metal tuning. The antenna consists of a center-feed circular patch antenna with a C-shaped slot as the driven element. To broaden the bandwidth and improve the realized gain, a parasitic circular disc and 13 circular directors are employed. The direction of polarization can be tuned by changing the location of liquid metal alloy contained in the tube. The relationship between the dimensions and the maximally achievable gain has been analyzed. The antenna has exhibited a -10 dB impedance bandwidth from 4.3 to 5.3 GHz (a fractional bandwidth of 21.2%). A 14.4 dBi gain is achieved at 5.3 GHz. The simulation and measurement results show good agreement with each other.

Index Terms—Yagi Antenna, Liquid Metal, Polarization Reconfigurable

I. INTRODUCTION

Reconfigurable antennas have been widely used in various fields such as mobile communications, radars and navigations. Polarization-reconfigurable antennas are desired in mobile communication systems as the reconfigurability in polarization helps reduce the loss due to polarization mismatch. To realize the polarization agile capability, electric control components such as p-i-n diodes or MEMS switches are often employed [1]-[9].

A new type of material that has been utilized in the recent few years to realize the reconfigurability is the liquid metal. One widely used liquid metal alloy is eutectic gallium 75% - indium 25% (EGaIn) or Galinstan, which presents liquid state at room temperature with a stable fluidity and has an electrical conductivity of 3.46×10^4 S/m [10]. In general, there are two methods of applying liquid metals to reconfigurable antennas. Firstly, the liquid metal can play the role of a switch [11]. Secondly, the liquid metal can serve as part of the radiation element [12]-[14]. For instance, reconfigurability can be achieved by adjusting the length, shape or position of the liquid metal. In [14], a three-element Yagi-Uda array with frequency reconfigurability based on liquid metal was proposed, where the length of each element was controlled by the liquid metal alloy contained in the capillary in order to operate at multiple frequencies. Liquid metal tuning technologies are also used in polarization-reconfigurable antenna [15]. However, the proposed polarization-reconfigurable antennas are narrow band and low gain.

Yagi antennas have the merits of high gain, unidirectional radiation, low cost and easy fabrication and have been widely used in wireless communication and radar systems [16], [17]. However, Yagi antenna generally has a narrow bandwidth. Many methods have been employed to extend the bandwidth of Yagi antenna mainly by altering

the structures of the driven elements [18] and adding stacked structures [19]-[22]. Broadband microstrip antennas have been extensively studied [23]-[28]. Introducing parasitic patch elements is a major technique that has been widely used [23],[24]. The typical electromagnetically coupled patch antennas have about 20% bandwidth and 8 dBi gain [23],[28]. The electromagnetically coupled rectangular patch antenna has been theoretically studied in depth [26], [27]. Three working regions have been identified, including: broadband region, abnormal region and high gain region. The impedance bandwidth in the broadband region mainly depends on the thickness of the dielectric substrate and the spacing between the driven patch and parasitic patch. A thicker dielectric substrate can achieve a maximum impedance bandwidth of 19.6%, while the maximum gain in the high-gain region can only reach 8.6 dBi.

In this paper, a polarization-reconfigurable wideband high-gain Yagi antenna based on liquid metal is reported. An improved center-feed circular patch and a parasitic patch are used to excite multiple disc directors. High gain and broadband impedance operations are obtained simultaneously. The direction of polarization can be easily tuned by changing the location of the liquid metal in the tube. This antenna could be used as the feed antenna of a reflector in radar or communication systems.

II. ANTENNA STRUCTURE AND DESIGN PRINCIPLES

A. Antenna structure

The configuration of the disc stacked Yagi is shown in Fig. 1(a). Different from the traditional Yagi antenna consisting of half-wavelength dipole driver, reflector and multiple directors, the antenna proposed here includes 13 circular metal discs as the directors and a patch antenna is used as the driven element. The latter is also where the tuning of the polarization direction by the liquid metal alloy takes place. This patch driver is shown in Fig. 1(b). It is essentially a center-feed circular patch. The inner circular patch with a radius of $r1$ and the outer ring patch of an outer radius of $r2$ are printed on a circular RO4350B substrate with a relative permittivity of 3.48 and loss tangent of 0.0037. The radius and thickness of the substrate are r and d , respectively. The other side of the substrate is the metal ground. The gap g between the primary radiated patches is 0.5 mm. Sitting on top of the patch is a cylinder with a radius of $r4$ and a height of $d1$, made of polymethyl methacrylate (PMMA) with a dielectric constant of 3.7. Inside the PMMA cylinder, a ring groove with a height of $d2$ is formed using a cutter. When this ring groove sits right above the ring gap g , a micro-fluidic ring channel is formed. About 1/6 of the channel is filled with a short section of liquid metal, which is sealed by liquid polytetrafluoroethylene (PTFE). These are injected through two Teflon tubes. The inner patch and outer ring patch are shorted at the location of the liquid metal bar. By pumping through syringes connected to the Teflon tubes, the position of the liquid metal bar can be moved. This changes the current path on the driving patch, and therefore the polarization direction. **Before installing the parasitic patch, the position of the liquid metal bar is observed under a microscope and the amount of PTFE injected through the needle is**

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recorded. Then the parasitic patch and directors are installed. The direction of antenna polarization is controlled by the amount of injected PTFE. It has to be said that a programmable micro constant current pump and an accurate cross polarization calibration procedure are required to produce a more precise look-up table and correlate the polarization direction with the injection amount of PTFE. Fig. 1(c) illustrates the 0° , 30° , 90° and 180° polarization direction states. A circular copper parasitic patch with a radius of r_3 and a thickness of d_3 is further stacked on top of the PMMA cylinder to improve the impedance matching and bandwidth.

(a)

(b)

(c)

Fig. 1. The structure of (a) the Yagi antenna with 13 direction units, (b) the driven element and parasitic patch (c) the polarization direction states.

Thirteen circular copper discs with the radius from r_5 to r_{17} and the spacing from d_5 to d_{16} are employed as directors. Each director is secured by foam cylinders (Cascell 50HF) with the dielectric constant of less than 1.1. The spacing between the first director and the patch driver is d_4 . The diameters of the directors varied slightly from 0.28 to $0.35 \lambda_0$ (λ_0 is the wavelength in free space at 5.3 GHz). The spacing between the adjacent directors is almost $0.2 \lambda_0$ which is smaller than the typical spacing ($0.25 \sim 0.3 \lambda$) in conventional dipole Yagi antennas. All elements of the antenna structure are stacked along Z-axis to guide the electromagnetic wave towards the direction of directors. A high gain of 14.5 dBi at 5.3 GHz is achieved. The -10 dB impedance bandwidth is from 4.3 to 5.3 GHz (a fractional bandwidth of 21.2%).

TABLE I
OPTIMIZED DIMENSIONS OF ANTENNA (mm)

r	d	$r1$	$r2$	$r3$	$d1$	$d2$
20	1.52	4	12	12	3	1
$d3$	$r4$	$d4$	$r5$	$d5$	$r6$	$d6$
1	8	10	10	10	8.5	11
$r7$	$d7$	$r8$	$d8$	$r9$	$d9$	$r10$
8.5	11	8.5	12	8.5	12	8.5
$d10$	$r11$	$d11$	$r12$	$d12$	$r13$	$d13$
13	8.5	13	8.5	13	8	13
$r14$	$d14$	$r15$	$d15$	$r16$	$d16$	$r17$
8	13	8	13	8	13	8

The antenna is excited at the center of the patch using a 50Ω semi-rigid coaxial cable. The whole geometry of the antenna has a rotational symmetry and the location change of the liquid metal does not affect the impedance matching. Continuous polarization adjustment covering a 180° range is achievable by tuning the liquid metal bar across the semi-circumference, as illustrated in Fig. 1(c).

Full wave simulation in CST is used to demonstrate and optimize the performance of the antenna. The dimensions after optimization are given in Table I.

B. Design Principles

Two resonant modes are excited in the proposed antenna, which is the key to the bandwidth expansion. Less than 5% impedance bandwidth was achieved in our previous work [15], with only one resonant mode excited effectively. In this work, two resonant modes are generated by the center-feed circular patch with a C-shaped slot and the parasitic patch.

It is known that the input impedance obtained from a central excitation of the patch antenna is close to 0. The liquid metal bar, which shorts the inner patch and outer ring patch, breaks the symmetry of the current distribution on the center-feed circular patch. This provides the possibility to achieve proper input impedance. A parasitic patch is introduced to improve the matching and bandwidth. There is an important difference between the conventional parasitic patch antenna [23] and the proposed antenna. Here the center-feed circular patch with a C-shaped slot was used to excite the parasitic patch whereas a small patch in the middle layer was used to excite the parasitic patch in the conventional design. The radius of the parasitic patch and its distance from the center-feed circular patch determine how effective both resonances can be excited.

The parameters of the driven element, shown in Fig. 1(b), are first analyzed. The relationship between $d1$, $r3$ and S_{11} is given in Fig. 2. It shows that it is very difficult to achieve wide bandwidth and good matching just by optimizing these two parameters. It was found that when $d1 = 3$ and $r3 = 12$, an -8 dB impedance bandwidth of 15% is obtained and the two resonant modes are excited approximately evenly. One limiting feature of the antenna is that the spacing value, $d1$, relative to wavelength is smaller than the conventional parasitic patch antenna. This restricts the bandwidth and matching. To overcome this, the first director was devised to enhance the matching and bandwidth. As shown in Fig. 2, when the first director is introduced, -10 dB impedance bandwidth reaches 4.2 - 5.35 GHz. It should be noted that the impedance bandwidth is less affected by other directors than the first one.

Fig. 2 The relationship between $d1$, $r3$ and S_{11}

The spacing of each disc directors is smaller than 0.25λ . The spacing (d) effects on gain and impedance bandwidth are shown in Fig. 3. Equal spacing is used in the simulations. It can be observed that the gain increases gradually as the spacing between antenna directors increases. However, the gain of the antenna decreases sharply beyond a certain threshold (25 mm). Impedance bandwidth first fluctuates with the spacing, and then decreases sharply when it is larger than 14 mm (about 0.25λ at 5.3 GHz). When the spacing exceeds a certain value, the gain increases slowly at a cost of a reduced impedance bandwidth. After optimization, the non-uniform spacing between 11mm and 13mm was applied in the final design. The magnetic coupling between the disc directors of the Yagi antenna is weaker than conventional linear Yagi antenna but the electrical coupling is much stronger. The electrical coupling coefficient increases as the spacing is decreased.

The induced current on the directors decays faster than that from the conventional linear element directors due to the weaker magnetic coupling which is shown in Fig. 4. This is mainly because the disc directors limit the magnetic coupling. The maximum gain of the proposed antenna is slightly higher than 14.5 dBi.

The current distribution on the first parasitic disc at different polarization states are shown in Fig. 5(a). The polarization direction is found to be parallel to the line connecting the center point of the inner circular patch and the middle point of the liquid metal bar.

The variation of the current at the center of each disc element is shown in Fig. 5(b) with the current at the driven element normalized. It can be observed that the closer the disc element is to the antenna terminal, the lower the current on it. The normalized current amplitude ripple is mainly caused by the terminal reflection of the traveling waves supported by the disc directors.

Fig. 3. The variation of gain and bandwidth with spacing.

Fig. 4. The electric field distribution of (a) the proposed Yagi antenna and (b) a conventional linear directors Yagi antenna.

The unloaded Q factor of the disc director is lower than linear director which is suitable for wideband application. However, the current on the disc directors drops quicker than the linear directors of the conventional Yagi antenna, which limits the maximum gain this type of Yagi antenna can achieve.

Fig. 5. (a) Current distribution on the first parasitic disc at different polarization angles (b) The normalized current amplitude at the center of the feed element and the subsequent discs of directors. The index 0 denotes the driven element.

III. RESULTS AND DISCUSSION

A. Simulated and Measured Results

The prototype antenna is shown in Fig. 6 with a total length of 161.5 mm. The performance of impedance matching was measured by a vector network analyser.

Fig. 7 illustrates the simulated and measured S_{11} results for the y-axis and x-axis polarization where two resonant modes are observed. The bandwidth of the measurement is slightly narrower and shifted to the lower frequency. This discrepancy mainly comes from two factors - the manufacturing tolerance and the length inaccuracy of the liquid metal in the micro-fluidic channel. The small discrepancy between the y-axis and x-axis polarization is caused by the position of the Teflon tubes in PMMA. The measured bandwidth covers 4.3-5.3 GHz (21.2%), which is wider than the conventional Yagi antenna. The two resonant modes on the driven element are effectively excited, which provides the basis for a wide impedance bandwidth. Optimized directors with low Q value are employed, which further improves the bandwidth. The conventional Yagi antenna of linear element normally exhibits an impedance bandwidth of no more than 10%, depending on the length and spacing of the elements [16], [20].

Fig. 6. The photograph of the prototype antenna.

The radiation pattern of the antenna was measured in the anechoic chamber. Fig. 8 shows the simulated and measured y-axis polarization radiation patterns in the E-Plane (yoz) and H-Plane (xoz) at 4.3, 4.9 and 5.3 GHz. The cross polarization is lower than -20 dB in the two principal planes over the whole band. The measured cross polarization is higher than the simulation result of -60 dB. This is mainly because the location of liquid metal bar is not very accurate in the measurement.

Fig. 7 The simulated and measured S_{11} of the antenna at (a) y-axis polarization and (b) x-axis polarization.

The simulated radiation patterns with the polarization of 0° , 45° and 90° at 4.9 GHz are shown in Fig. 9. As expected, they are well consistent among different polarization angles because of the rotational symmetry of the antenna. The co-polarization and cross-polarization pattern in $\Phi=45^\circ$ plane are not perfectly symmetric due to the structural asymmetry.

Fig. 8 Simulated and measured y-axis polarization patterns in the E-plane (left) and H-plane (right) at (a) 4.3 GHz, (b) 4.9 GHz and (c) 5.3 GHz.

Fig. 9 Simulated patterns with the polarization of 0°, 45° and 90° at 4.9 GHz: (a) E-plane; (b) H-plane.

The simulated and measured gain at y-axis polarization is shown in Fig. 11. Good agreement is achieved between simulation and measurement. The measured gain is slightly lower than simulation, which is mainly caused by the error of fabrication and the unaccounted losses from the cables and the device. There are 3 dB gain difference in the impedance bandwidth as shown in Fig. 10. The reason is that the gain optimization of Yagi antenna focuses on 5.3 GHz, so the spacing and size of the directors are no longer optimal at the other frequencies. The gain performance with the different number of directors are analyzed, as shown in Fig. 11. It can be observed that the gain of the yagi antenna increases gradually with the increase of the number of directors. At the same time, the gain difference between 5.3 GHz and 4.3 GHz is 1.7 dB (4 directors), 2.1 dB (6 directors), 2.5dB (8 directors), 2.7dB (10 directors) and 3.2dB (13 directors), respectively. The gain difference increases with the increase of the number of directors.

Fig. 10 The simulated and measured gain at y-axis polarization.

Fig. 11 Gain analysis at different frequencies.

The number of directors has a direct impact on the gain of the Yagi antenna. Keeping the other structural parameters constant, the optimized maximum gain against the number of directors at 5.3 GHz has been investigated through simulation and shown in Fig. 12. It can be observed that the gain increases with the number of directors but starts to level off after the eighth director added. The gain is increased to 12.7 dB using eight directors, 4 dB higher than that of only one director. When the 13th director is introduced the gain reaches 14.4 dB, which is 1.7 dB higher than that from eight directors. The gain of this antenna is limited to about 15 dB. Further directors will not increase the gain significantly as the induced current decreases as the number of inductors increases.

Fig. 12 The maximally achievable gain against the number of directors at 5.3 GHz.

B. Parameter Analysis

Keeping the dimensions of the first three directors (given in TABLE I) unchanged, Fig. 13(a) shows the effect of the fourth director spacing $d7$ and the radius $r8$ on the impedance matching. The nearest and farthest directors from the first three directors are the object of study. The effect of the other directors between these two falls somewhere in between these two results. We optimized the whole antenna including the directors spacing and radius based on these results.

Fig. 13 The S_{11} of the antenna with different director spacing and radius at (a) the fourth director and (b) the thirteenth director.

The bandwidth of the antenna becomes narrower and the impedance matching level worsens with the spacing between the directors

increasing from 0.2 to 0.45λ (λ is the wavelength in free space at 5.2 GHz). A better impedance matching level can be obtained when the spacing of $d7$ is around 0.2λ which is smaller than the spacing of $0.25 \sim 0.3 \lambda$ in conventional dipole Yagi antenna. This is mainly because electrical mutual coupling dominates between the discs. The effect of the radius $r8$ of the fourth director is also studied. The spacing of $d7$ keeps constant at around 0.2λ . The radius $r8$ is changed from 0.15 to 0.25λ . The impedance matching performance deteriorates when $r8$ is larger than 0.2λ . The impedance matching level is optimal when the radius is around 0.15λ . It can be observed that the radius of the director is much more important for the S_{11} characteristic of the antenna than the spacing between directors.

Similar parameter study is repeated for the radius $r17$ and spacing $d16$ of the thirteenth director. Fig. 13(b) exhibits that the impedance matching is stable, indicating that this director has little influence as the current on it becomes very weak.

Fig. 14 illustrates the effect of the radius and spacing of the fourth and the thirteenth directors on gain. The gain is improved by 0.25 dB at 5.2 GHz with the spacing of $d7$ and the radius of $r8$ increases from 0.2 to 0.45λ and 0.15 to 0.25λ respectively. However, this is at the expense of the impedance matching performance. Fig. 14(b) shows the thirteenth element barely affects the gain.

Fig. 14 The gain of the antenna with different director spacing and radius at (a) the fourth director and (b) the thirteenth director.

Optimizing the spacing between the directors can maximize the gain with the same total length of the Yagi antenna. The ideal parasitic element spacing of the circular patch yagi antenna is smaller than the traditional wire Yagi antenna. One example is given in Table III to analyze the relationship between the gain and parameters of the circular patch Yagi antenna. The optimized gain results of five and seven directors with the overall length of 1.6λ are given in TABLE III. Keeping the size of the first three directors constant, the fourth and fifth directors have a radius of 0.15λ and the director spacing of $d7$ and $d8$ are 0.45λ . The dimensions of the seven-director Yagi antenna have been given in TABLE I. The gains of the two antenna structures are 11.8 dB and 12.5 dB at 5.2 GHz respectively. Under the same overall length of the antenna, the gain increases faster by adding more directors than by increasing spacing between directors. Fig. 15 Shows the E-Plane and H-Plane 3 dB beamwidth of the same length antenna with 5 directors and 7 directors respectively. It can be seen that the 3 dB beamwidth decreases as frequency increases. It is clear that

antenna with 7 directors has a narrower beamwidth than antenna with 5 directors both in E-Plane and H-Plane.

TABLE III

GAIN OF DIFFERENT DIRECTOR SPACING AT THE SAME LENGTH OF YAGI ANTENNA

Length of Yagi (λ)		1.6	
Number of directors		5	7
Spacing between directors (λ)	$d4$	0.18	0.18
	$d5$	0.18	0.18
	$d6$	0.19	0.19
	$d7$	0.45	0.19
	$d8$	0.45	0.21
	$d9$	N/A	0.21
	$d10$	N/A	0.23
Gain(dB)		11.8	12.5

In summary, the value of spacing between directors is set to 0.2λ based on impedance matching performance and higher gain for the Yagi antenna with the fixed overall length. The radius of directors is chosen to be 0.15λ which mainly depends on the impedance matching performance of the antenna.

Fig. 15 Simulated 3dB beamwidth of a 5-director and a 7-director Yagi antenna

IV. CONCLUSION

A polarization-reconfigurable antenna is developed with a wide relative bandwidth of 21.2% and a high gain of 14.4 dBi at 5.3 GHz. Polarization reconfigurability is achieved by adjusting the location of the liquid metal alloy bar in the micro-fluidic ring channel of the patch driver. The measurement results agree well with simulation results. In addition, the effects of director spacing and radius on impedance matching and gain are studied. The design principles of the directors of disc stacked Yagi antenna are proposed.

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