A High-Efficiency Reconfigurable Element for Dynamic Metasurface Antenna

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ABSTRACT A high-efficiency reconfigurable element for dynamic metasurface antennas (DMA), consisting of a complimentary electric-LC (CELC) resonator fed through the cavity from a waveguide slot, is proposed in this paper, with positive- intrinsic-negative (PIN) diodes loaded to realize the coding performance. To begin with, the low efficiency problem of a traditional CELC element is demonstrated before the introduction of the proposed element. Subsequently, an equivalent circuit is illustrated to analyse the resonant performance, with extensive parametric study for verification. The proposed element has a low ohmic loss when the diode is switched on, 25 times less than the traditional element. Furthermore, the radiation efficiency of a DMA with 10 proposed elements is compared with a traditional design, showing a significant efficiency improvement from 25% to 75% when half diodes are switched on. Finally, measurements are conducted to verify the feasibility of the dynamic element to achieve radiation ON and OFF states, showing a 12 dB radiation gain difference between two states.

INDEX TERMS Dynamic metasurface antenna, high efficiency, metasurface, PIN diode, reconfigurable.

I. INTRODUCTION Metasurfaces, with planar structure, can modulate the electromagnetic wave in unprecedented manners, which has attracted much attention from the academic and the industrial communities [1], [2]. By employing metasurface technology, the electromagnetic properties such as the phase, amplitude and polarization can be manipulated to realize different functions: beam steering [3], [4], generation of radio vortex [5], [6], frequency selective surface (FSS) [7], [8], energy selective surface (ESS) [9], [10], computational imaging system [11], etc.

By integrating a tuning mechanism into each metamaterial element, dynamic metasurface can have a further control over the radio waves, which had been widely used in transmitters [12], reflectarray [13] and so on. With the optimism of the coding, the surface can generate the radiation patterns of interest. However, the feeder used in the transmitarray or reflectarray increases the profile, which is not suitable for application with compact space. With the resonant radiators fed by transmission line (e.g., waveguide or microstrip line or parallel plate waveguide), the dynamic metasurface antenna (DMA) [14], [15] can be easily integrated in a thin planar structure, making it more attractive for the industrial application. A portion of the guided wave radiates through the elements to free space when the element is configured in a radiation state, while no energy radiates when the element is switched to a non-radiation state. The manipulation of radiation pattern can be obtained by using the specific holography formula to code the surface.

The thin reconfigurable dynamic metasurface antennas had been explored to be used in satellite communication [16], near-field computational imaging [17], synthetic aperture radar (SAR) system [18], security screen technology [19], and to name a few. In comparison with the phased array or electrical scanned antenna (ESA) [20], DMA can provide comparable performance with extreme low cost and complexity. Approaches to achieve the tune performance include the employment of liquid crystal [21], Micro-Electro-Mechanical System (MEMS) switch [22],
positive-intrinsic-negative (PIN) diode [23] or varactor diode [24], of which the liquid crystal and MEMS have high fabrication cost and processing complexity while varactor diode has a high loss. To trade off the design complexity, fabrication cost and the efficiency, PIN diode is a good choice for the DMA designs, which shows high potential for microwave applications. Complimentary electric-LC (CELC) element with PIN diodes loaded is commonly used in DMA technology. The transmission and reflection characteristics of rectangular CELC metamaterial element without PIN diodes had been investigated extensively [25]. A multiscale dipolar interpretation for arrays of complementary elements was made to extract the effective polarizability [26], providing the model theory. To improve the radiation efficiency of the element, a modified CEL radiators was presented to maintain low ohmic loss [27]. Loading PIN diodes to CELCs enables the tuning performance of the metasurface. Serving as the building block of DMA, a rectangular CELC resonator with PIN diode was patterned into the upper conductor of a transmission line, based on which metamaterial aperture is capable of dynamic beam-forming [23].

The aforementioned reconfigurable CELC elements can provide the dynamic performance, however, has a obvious disadvantage of low efficiency as a whole. The main reason is that when the patterned PIN diode is switched on, a mount of current will flow directly through diode, leading high ohmic loss due to the parasitic resistor. Given that a portion of the elements in the DMA are switched on, therefore, the total radiation efficiency is pulled down. To improve the overall radiation efficiency, herein a high-efficiency reconfigurable metamaterial element based on an elliptical CELC element is demonstrated. On contrast to patterning the CELC on the waveguide surface, our design introduces a waveguide slot and a back cavity to feed the CELC element. When it is switched on, the current does not pass through the diode directly, thus low ohmic loss can be ensured.

This paper is organized as follows. The DMA technology is first introduced in Section I. Section II illustrates the high ohmic loss problem of traditional reconfigurable CELC element. In Section III, the structure of the high-efficiency reconfigurable element is described. Subsequently, an equivalent circuit is built in Section IV, with extensive parameter analyses. The measurement is conducted to verify the feasibility of the proposed element in Section V. The conclusions are drawn in Section VI.

II. LOW EFFICIENCY PROBLEM OF TRADITIONAL ELEMENT AND STRUCTURE OF THE PROPOSED ELEMENT

A. LOW EFFICIENCY PROBLEM

To realize dynamic radiation pattern, the element in DMA should have a significant power difference between radiation ON and OFF states, as shown in Fig.1, which had been achieved in the traditional DMA element. Besides, low loss at each state is required to achieve a high radiation efficiency.

The loss of the traditional DMA element at radiation ON state (corresponding to diode-OFF state) can be ensured, however the high loss problem at radiation OFF state (diode-ON state) is currently a bottleneck problem for DMA. When the PIN diode is switched and the current flows through it, leading a high ohmic loss and low efficiency for DMA consisting of both switched-on and switched-off diodes.

To illustrate the low efficiency problem, here a traditional elliptical CELC element is presented and simulated. Please note that here the radiation efficiency does not refer to total efficiency. Instead, we mean the efficiency without consideration of ports impedance matching. Fig.2 shows the prospective and top view of traditional element which patterns the CELC shape directly on the top wall of a substrate integrated waveguide (SIW) with two PIN diodes (MADP-000907-1420) loaded. The SIW waveguide is based on substrate F4BTME, which has a width of 11 mm and height of 1.5 mm with a dielectric constant of 3.5. The simulation parameters of the structure are: $d_{cut} = 1$ mm, $d_{gap} = 0.15$ mm, $r_1 = 2.4$ mm, $r_2 = 2$ mm. The biased line is placed across with the central patch where the E-field is marginal, thus the influence of biased line can be kept in a low level, which will be further discussed in this section. The traditional design has been optimized to resonate at around 12.5 GHz which covers part of satellite communication spectrum. In addition, a DMA at this band has a more compact size compared to
lower frequencies and less soldering complexity compared to higher frequencies.

Fig.3 gives the power consumption of diode-ON and -OFF state in terms of the dielectric substrate loss, metal loss, lumped element (PIN diode) loss and the radiation power, which are analyzed by CST full wave simulation. The simulated source power is 0.5 W. Please note that the reflected wave to port 1 and transmitted energy to port 2 are not included in Fig.3. It can be observed in Fig.3(a) that the element has an obvious radiation power at diode-OFF state with low loss, serving as a radiator in DMA. While at diode-ON sate, the element as non-radiator has suppressed radiation. But, the loss caused by the lumped element is pretty high as shown in Fig.3(b), up to 0.22 W at 14.5 GHz. When embedded in DMA, the ON-diodes will consume part of energy, therefore drawing down the average efficiency. The current flows directly through the diodes at ON-state as shown in Fig.4(a) and the boundary condition is nearly continuous in the propagating direction, therefore, the current distribution is almost the same as that of the waveguide without CELC shape pattern. Since the current continuity is not broken, the induced E-field on the surface is marginal as shown in Fig.4(b). When the diodes are switched off, the element is at resonant state, hence strong E-field is induced at the gap. The current distribution is also strong, but this does not mean that a high strong current flows through the diodes. Instead, the induced E-filed is excited as displacement current to keep the current continuity condition. The more diodes switched on, the lower the overall efficiency it has. Thus, to improve the total radiation efficiency of the DMA, a high-efficiency element at both ON and OFF states should be developed.

It is worth noting that the biased line, crossing with the central patch, does not affect the radiation pattern. For verification, here the S-parameters and the radiation patterns for traditional elements with and without biased line are simulated as shown in Fig.5. It can be observed that both S-parameters are almost the same, as well as the radiation patterns of elements at diode-OFF state. It is noted that the S11 at diode-OFF state is quite high, which may mislead to an unreasonable conclusion. The element has a high Q factor and the impedance can not be matched well with only single one. But a DMA consisting of specific number of the elements can satisfy the impedance matching condition after optimization. In this way, it is reasonable that the single element has a poor impedance matching. The element can be regarded as a middle stage of the dynamic metasurface antenna. Hence the impedance matching should be considered carefully when forming a dynamic metasurface antenna (DMA) with elements rather at the first beginning of the element design. Despite E- and H-plane radiation patterns of elements with and without biased line at diode-ON state are different as shown in Fig.5, the gains are kept in a low level which do not affect the property of DMA significantly. It can be concluded that the biased line poses marginal effect on the element. Hence for a more direct observation, hereafter the simulations of elements are based on structure without biased line.

**B. STRUCTURE OF PROPOSED METAMATERIAL ELEMENT**

As shown in Fig.6, the proposed metamaterial element consists of three main parts, namely a CELC pattern unit, a back cavity and a waveguide slot. Instead of using the guided
wave to feed the CELC unit, the proposed design feed the CELC radiator through a back cavity from a waveguide slot. By loading the PIN diodes on the CELC element, tuning performance can be achieved. The employment of the waveguide slot and back cavity in the design helps cut off the current from waveguide surface to the diodes, thereby suppressing the current through the diode and decreasing the power loss at diode-ON state. The parameters of the structure are displayed in Fig.6. The waveguide configuration is the same as that of Fig.2. Substrate F4BTME with thickness of $h_{\text{sub}}$ is used in the back-cavity layer. The polarization of the element is $x$-polarization. The simulation of $y$-polarization is similar to that of $x$-polarization, therefore, for conciseness it is not stated here.

III. SIMULATIONS ANALYZES

In this section, the power consumption and the field distribution are investigated to verify the feasibility, and an equivalent circuit is built to model the element with extensive parametric study. Furthermore, the radiation efficiencies of DMA comprised of 10 proposed elements are simulated and compared with a traditional design.

A. POWER CONSUMPTION AND FIELD DISTRIBUTION

Set the parameters configuration as below: $d_{\text{cut}} = 0.7 \text{ mm}$, $d_{\text{gap}} = 0.47 \text{ mm}$, $r_1 = 2.4 \text{ mm}$, $r_2 = 2.8 \text{ mm}$, $h_{\text{sub}} = 1 \text{ mm}$, $l_c = 6.4 \text{ mm}$, $l_w = 4.9 \text{ mm}$, $s_l = 5.5 \text{ mm}$, $s_w = 1.7 \text{ mm}$. Fig.7 gives the breakdown of power consumptions of proposed design at diode-OFF and ON-state (corresponding to radiation ON and OFF states). Please note that the parameters are optimized towards to the same goal of the
traditional design, namely making a resonance at 12.5 GHz. It can be observed in Fig.7 (a) that resonance occurs at central frequency, with high radiation power up to 0.21 W at diode-OFF state while other loss keeping in a low level. When the diodes are switched on, the radiation power as well as other losses are marginal, from which only 0.006 W ohmic loss in diodes can be achieved, above 25 times less than the 0.15 W loss of traditional element as shown in Fig.3 (b). In other words, the ohmic loss of diodes are deeply suppressed, thus the radiation efficiency of coding surface antennas can be improved. Fig.8 gives the current and E-field distribution of the proposed design. In comparison with Fig.4, it is noted that at diode-ON state less current flows through the diodes as shown in Fig.8 (a), verifying the feasibility of proposed structure to suppress the ohmic loss of diodes at ON-state. The current and E-field at diode-OFF state shows the resonant radiator property. Specifically, the current of diodes in traditional CELC element is 0.16 A as shown in Fig.9, while the proposed design only has a current of 0.01 A. The reason why the current flows through the diodes is less than the traditional element at diode-ON state is that the slot and the cavity cut off the direct path of the current from the waveguide surface to the CELC unit. This can be seen from the current distribution inside the cavity as shown in Fig.10.

B. EQUIVALENT CIRCUIT AND PARAMETRIC STUDY
For ON or OFF state, the used PIN diode MADP-000907-1420 [28] can be modeled as a series of lumped resistance (R) and inductance (L) or capacitance (C) and inductance (L), respectively, as shown in Fig.11. At OFF-state, the PIN diode can be mainly modeled as an equivalent capacitance C1, while the resonant radiator can be modeled as the radiation resistor R1. C2 represents the equivalent capacitance effect of gaps around the diodes. Also, the metal parts between the CELC pattern and the waveguide surface below the back cavity contribute the capacitance C3. The central metal part in the CELC pattern makes contribution to the inductance L.

The capacitive effect of the structure is studied in Fig.12. As shown in Fig.12 (a), the resonant frequency increases with the gap width $d_{\text{gap}}$ as the equivalent capacitance decreases with the width of gap. With regard to the height of the back cavity, the capacitive effect also decreases with the height, hence the resonance performance has a similar trend with that of gap width as shown in Fig.12 (b). The resonant property has a roughly linear relation with the gap width, but a non-linear relation with the height. That is because the equivalent capacitance C2 is not linear with the height. The inductive
The capacitive effect is mainly determined by the average waist width $w_1$ of the central curved isolated metal patch. The narrower the patch is, the higher inductance it has. The resonance performance for different waist widths $w_1$ is shown in Fig. 13, which demonstrates that the resonance increases with $w_1$. Overall, the capacitive and inductive effect on the resonance performance agree with the formulation of the equivalent circuit.

Furthermore, the offset position of the element with respect to the central line is also studied, which can be seen from Fig. 14. It can be observed that the resonance frequency increases with the offset value. The radiation power for CELC unite close to the central line is obviously smaller that that of position far from the central line, which is similar with the waveguide slot antenna. Hence, when designing the element, the offset position should also be considered.

C. RADIATION EFFICIENCY COMPARISON BETWEEN 1D DMAS WITH TRADITIONAL AND PROPOSED ELEMENTS

To investigate the influence of the element on the radiation efficiency of DMA, two DMAs with traditional and proposed elements are simulated, respectively. Each array has 10 elements and the spacing distance is half waveguide wavelength. The radiation efficiencies of arrays with different number of switched-off elements is shown in Fig. 15. Elements in the first part of the DMA are switched off. For example, when referring to 3 elements off, it means that the first
3 elements (index:1,2,3) are switched off. It is noted that a high radiation efficiency up to 86% can be achieved with 10 traditional elements switched off. However, the radiation efficiency drops by 15% when one element is switched on. Even worse, this value has a significant decline to below 25% when half of elements are at diode-ON state. In a word, the radiation efficiency of traditional array with switched-on elements is pretty low. Fig. 15 (b) gives the radiation efficiencies of array with the proposed elements. Similar efficiency can be achieved when all the elements are at diode-OFF state. The radiation efficiency slightly decreases with the number of switched-on elements. Specifically, for array with half elements switched on, the efficiency is about 3 times of traditional one, reaching up to about 75%. It is noted that the traditional array experiences a more significant decrease of the radiation efficiency when the elements are switched on. From the simulation result, it can be concluded that the employment of proposed element improves the radiation efficiency of the array significantly.

For verification of the dynamic performance, here another DMA composed of 32 elements with 5 mm spacing (around $1/5\lambda$) is simulated to achieve beam scanning performance from $-40^\circ$ to $40^\circ$, as shown in Fig.16. Please note that the element space should not be too large otherwise the DMA will shows the frequency-beam scanning performance, and it can not achieve beamscanning at a fixed frequency. The element code configuration of the DMA can be calculated with the methods in [16], [28]. Traditional beamforming uses the continuous phase and amplitude weight, while in DMA the element can only achieve discrete phase or amplitude weight. Therefore, common DMA technology uses the discrete weights to approximate the continuous weights and achieve beamforming performance. It can be seen in Fig.16 that the beams scanning performance can be obtained, however with steering error which can be further calibrated. The gains are shown in the inset. It is noted that the maximum gain (14 dBi) is not achieved at the normal direction but at $20^\circ$, which is different from traditional beamsteering technique. This is due to the weight quantization error from the 1-bit coding formulation. Similar with other DMA designs, the simulated DMA also has high side lobe level problem, ranging from $-10$ dB to $-3$ dB. Specifically, the side lobe for steering angle $40^\circ$ is $-3$ dB, while the value for angle $-10^\circ$ is $-10$ dB. As the element number of the DMA increases, the impact of the quantization error of the weight on the beamforming can be improved with the overall code optimization [16], hence the sidelobe can become lower. There are several beamforming codes that can steer the beam in...
a specific direction. Hence, we can choose a code that has low side lobe as the configuration of the DMA. Another way to reduce side lobe is using 2D DMA technology with large number of elements.

IV. MEASUREMENT RESULTS

To verify the feasibility, the proposed element is fabricated as shown in Fig.17, which uses the ground-coplanar waveguide (GCPW) as transition. The proposed element is comprised of two parts which are installed by the plastic screws. The biased lines are soldered as shown in the Fig.17 and placed orthogonally to the PIN diodes. By applying a DC voltage, the state of diodes can be configured. The setup of S-parameter and radiation pattern measurement are shown in Fig.18. We use a DC source to control the biased voltage when measuring the S-parameter for different states. Given that the voltage of a battery (1.5 V) is slightly larger than the starting-up voltage (1.3V) of the diodes and the equivalent circuit of the diode is not affected a lot, we use a battery instead of a bulky DC source to achieve diode-ON state in the measurement of radiation. The reflection and transmission coefficients of the proposed element at different states are shown in Fig.19. As shown in the green frame region, the band of interest is from 12.2 GHz to 12.8 GHz. From the transmission result, a measured resonance at 12.3 GHz can be observed at diode-OFF state, implying that the element is at radiation state since the main part of transmission loss of our design at diode-OFF state is the radiation. While at diode-ON state the element is at radiation-OFF state and it works as a transmission line, therefore the transmission loss is low as shown in Fig.19 (a). When the element works as a transmission line, it does not radiate and the reflection coefficient should be low to ensure the impedance matching, which agrees well with the simulated and measured S11 (below −14 dB) at diode-ON state as shown in Fig.19 (b). While at diode-ON state the element is at radiation-ON state and it works as a transmission line, therefore the transmission loss is low as shown in Fig.19 (a). When the element works as a transmission line, it does not radiate and the reflection coefficient should be low to ensure the impedance matching, which agrees well with the simulated and measured S11 (below −14 dB) at diode-ON state as shown in Fig.19 (b). While at diode-ON state the element is at radiation-OFF state, which makes the impedance matching worse. As a result, the reflection coefficient at diode-OFF state is high (above -10 dB), from which it can be observed that the measurement shows a similar trend with the simulation, despite differences exist between the measured and simulated results. This is because when installing the multi-layer design layer by layer in a manual manner, the misalignment between layers causes the differences. The poor soldering of PIN diodes to the PCB board also affects the measurement result. The normalized radiation patterns of the proposed element are plotted in Fig.20. The gain of element is 2.1 dB at diode-OFF state. It is learned that the radiation power of E-plane and H-plane at diode-OFF state is 12 dB larger than that of diode-ON state, satisfying the property of DMA. There are ripples in the measured radiation pattern at radiation-ON state, which maybe due to the long cable that causes the reflection and affects the radiation pattern. As for the radiation-OFF state, the contact of the layers is not tight which causes the radiation leakage, therefore, leading the measured radiation pattern higher than simulation.
V. CONCLUSIONS
The low efficiency of traditional CELC element in DMA was firstly illustrated, showing high ohmic loss when the diodes are switched on. Subsequently, element consisting of waveguide slot, back cavity and CELC pattern was proposed to improve the radiation efficiency, with low ohmic loss less than 25 times. Furthermore, radiation efficiency comparison of arrays with traditional and the proposed elements was made, demonstrating high efficiency of the proposed structure. Finally, experimental results have shown a 12 dB gain reduction when switching the elements between ON and OFF states, which is in accordance with DMA applications.

The designed high-efficiency element makes the DMA technology more practical, which can be used in the wireless communication, imaging, security screening, and etc. Based on the proposed element, further researches will focus on the study of high-efficiency 1D and 2D DMAs to achieve dynamic beam steering and other applications.

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