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Liquid Crystal-Based Wideband Reconfigurable Leaky Wave X-Band Antenna

DI JIANG¹, XIAOYU LI¹, ZIHAO FU², PUHANG RAN¹, GUOFU WANG³,
ZHI ZHENG¹, (Member, IEEE), TIANLIANG ZHANG², (Member, IEEE),
AND WEN-QIN WANG¹, (Senior Member, IEEE)

¹School of Information and Communication Engineering, University of Electronic Science and Technology of China, Chengdu 611731, China

²School of Aeronautics and Astronautics, University of Electronic Science and Technology of China, Chengdu 611731, China

³School of Electrical and Information Engineering, Guangxi University of Technology, Liuzhou 545006, China

Corresponding author: Zihao Fu (429166064@qq.com)

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ABSTRACT In this paper, a pattern and frequency reconfigurable leaky wave X-band antenna based on liquid crystal is designed. The frequency sweep characteristics of traditional leaky wave antennas are replaced by electrical properties of liquid crystal materials. Through the liquid crystal tuning, the main lobe pattern is deflected by 25 degrees at a frequency shift of 1GHz, where the liquid crystal tuning is saturated at 20V bias voltage. The relative frequency reconfigurable bandwidth is 19%, the relative pattern reconfigurable bandwidth is 9.3% and the maximum gain is 10dBi. Moreover, the pattern and frequency response are well preserved during the tuning.

INDEX TERMS Half mode corrugated substrate integrated waveguide (HMCSIW), leaky wave antenna, reconfigurable antenna, liquid crystal.

I. INTRODUCTION

With fast development of wireless communication nowadays, antenna reconfiguration is increasingly emphasized for engineering applications. The operating antenna frequency band and pattern characteristics are required to vary with the specific requirements such as microwave and satellite communication systems. At present, non-real-time static and real-time dynamic reconfiguration methods are mainly used in the literature. One method is to statistically adjust the antenna index with microwave switching devices. Another one is realized by loading dynamic tunable media.

Liquid crystal (LC), as a new kind of electro-tuning material, has good dielectric properties and tuning ability in high frequency microwave and millimeter wave band [1]. In [2], [3], using inverted microstrip, the integration of liquid crystal bias circuit with microstrip is realized. In [4], an electrically modulated directional reconfigurable

leaky wave antenna loaded with liquid crystal material is proposed.

Substrate integrated waveguide (SIW) structure is an equivalent waveguide in microstrip technology. The equivalent waveguide wall is formed by the inductive metallized through-hole and the copper clad layer on the upper and lower surfaces. However, since the SIW circuits are equipotential, it is impossible to bias the liquid crystal layer. In [3], a novel kind of substrate integrated waveguide structure used for LC circuit is proposed. However, the structure reduces the tuning ability of liquid crystal. Through the traditional SIW short-circuit inductance properties, the hole is equivalent to 1/4 wavelength open circuit capacitance. The new corrugated substrate integrated waveguide (CSIW) circuit can realize unequal potential of signal line and ground, thus the tuning of liquid crystal bias voltage can be realized. It can be seen from literature [5] that CSIW replaces the through-hole side wall with a quarter-wave short column and has $TE_{1,0}$ mode propagation characteristics similar to SIW. At the same cut-off frequency, CSIW is 67% wider than SIW. In order to reduce the width, the specimen can be folded to form a so-called half-mode CSIW (HMCSIW).

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In this paper, a novel type of HMCSIW pattern and frequency reconfigurable leaky wave antenna is proposed. The antenna is miniaturized by HMCSIW processing and an H-shaped slot array with 1×5 is etched on the antenna surface. By tuning the equivalent permittivity of the liquid crystal materials at the RF port, the main lobe pattern is deflected by 25 degrees to achieve the pattern reconstruction. On the other hand, the single frequency shift of the antenna is 1 GHz by tuning the liquid crystal. Note that, in the tuning process, the frequency response pattern corresponding to a single frequency point is well preserved.

II. THEORETICAL CONSIDERATIONS

A. HMCSIW DESIGN

SIW circuit structure is equivalent to a series capacitor and a shunt short-circuit grounding high-pass filter by circuit analysis. Therefore, short circuit inductors can be replaced by $\lambda_g/4$ open circuit capacitors to form the CSIW structure. Because the open circuit capacitance replaces the short-circuit inductance, the potential of signal line and metal ground are not equal. Like traditional liquid crystal invert microstrip circuit, LC tuning can be achieved by injecting LC into the dielectric layer between the signal line and the metal ground and adding low frequency bias voltage to the RF port [6]. Like the traditional SIW architecture, CSIW supports dominant mode $TE_{1,0}$ mode transmission. Therefore, due to the symmetry of $TE_{1,0}$ mode electric field distribution, CSIW can be converted to HMCSIW structure by half mode processing to reduce the circuit size [7]. The difference is that the CSIW structure cannot realize the waveguide because there is no equivalent wall. The dominant mode electric field distribution of SIW, CSIW and HMCSIW can be obtained through full wave simulation software HFSS, as shown in Fig.1. Both CSIW and HMCSIW structures can effectively transmit $TE_{1,0}$ and $TE_{0,5,0}$ mode, and are well suitable for liquid crystal circuits.

B. H-SHAPE RADIATION GAP

H-slot is a variant of cross-slot, which is equivalent to adding a displacement current slot on the basis of cross-slot, so it has higher leakage rate, and the waveguide slot antenna loaded with H-slot has wide angle scanning characteristics from side to end [8]. Different from [7], the H-slot CSIW structure is used to realize broadband radiation characteristics, which provides bandwidth support for liquid crystal tuning. As shown in the Fig.1, the dispersion curve of HMCISW waveguide is loaded with H-slot by CST eigenmode solver. It can be seen from the figure that the HMCSIW waveguide loaded with H-shaped gaps has dispersion changes from fast waves to slow waves, and the dispersion characteristics of H-shaped gaps move towards slow waves with the increase of frequency. Before and after frequency tuning, the H-slot antenna array is in the right-hand region, that is to say, the radiation beam of H-slot antenna array is biased to the load, which

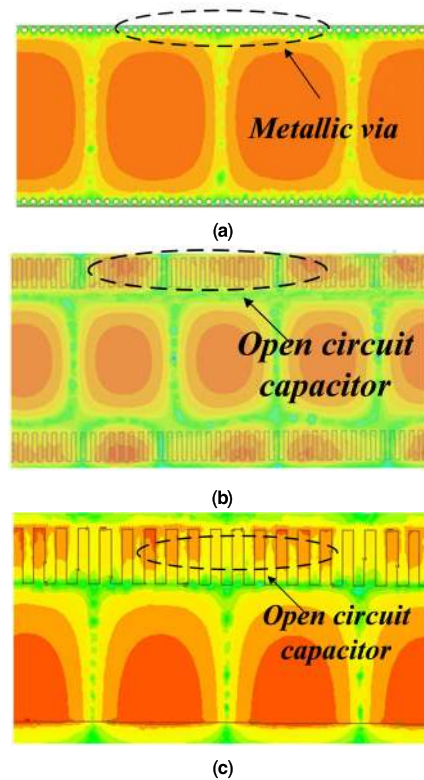


FIGURE 1. Different structures of SIW and corresponding electric field distribution (a) SIW, (b) CSIW, and (c) HMCSIW.

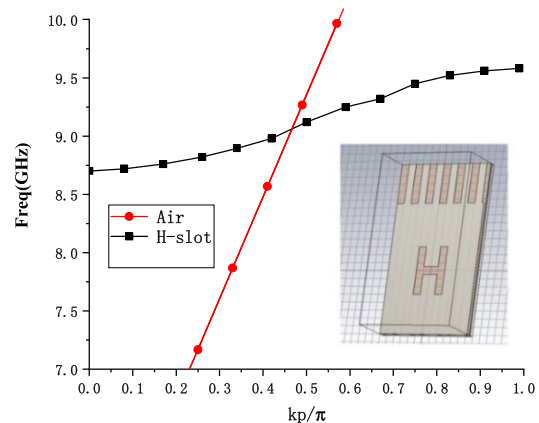


FIGURE 2. The dispersion curve of H-slot.

is consistent with the traveling wave direction. With the increase of frequency, the dispersion of H-slot moves to slow wave, and the deflection angle of antenna should shift to transmission direction with the increase of frequency.

Considering the consistency of LC packaging and the coating process of orientation agents, the antenna area is restricted. Therefore, in this paper only the 1×5 H-shape slot array, as shown in Fig.3, is simulated and measured.

The proposed antenna structure is shown in Fig.4, which consists of 3 layers. First, the inverted microstrip line is formed on the top dielectric substrate. In addition,

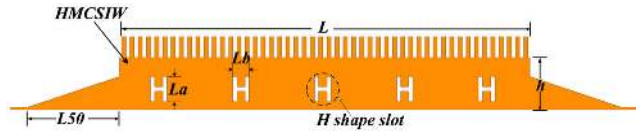


FIGURE 3. Layout of proposed antenna circuit.

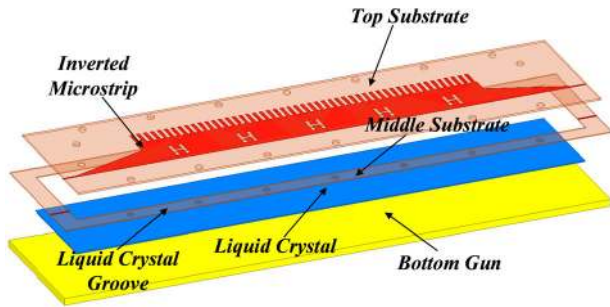


FIGURE 4. Proposed antenna structure model.

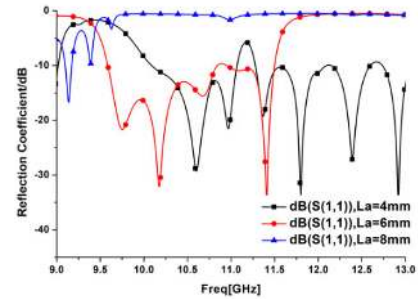
the rectangle liquid crystal groove is milled out of the intermediate substrate to accommodate the liquid crystal, and the 50Ω microstrip lines are etched at both sides, while the lowest level is metal. Due to the friction problem of liquid crystal alignment agents, the thickness is generally 1.1mm.

As shown in Fig.5, while loading the H shape gap, it is equivalent to produce defected ground structure. Therefore, the HMCSIW structure will produce stopband and narrow the bandwidth. It is seen from Fig.5 that, the parameter L_a and h affect the bandwidth and resonant point of the designed X-band antenna, as shown in Fig.5(a), while L_b , L and L_{50} affect its in-band matching, as shown in Fig.5(b)-(e).

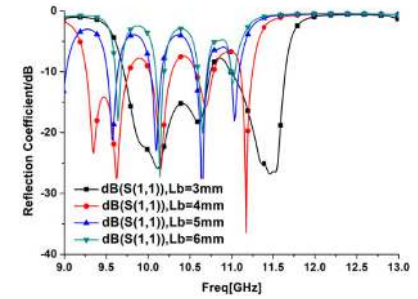
III. RESULTS AND DISCUSSION

The antenna has good matching bandwidth and radiation characteristics under the optimized parameters: $L=100\text{mm}$, $h=12.5\text{mm}$, $L_{50} = 22.5\text{mm}$, $L_a = 5.8\text{mm}$ and $L_b = 3.4\text{mm}$. Liquid crystal technology is expected to guarantee the deflection of liquid crystal molecules. To ensure the deflection of liquid crystal molecule, the alignment agent should be applied to the signal line and metal surface according to the liquid crystal technology. The substrate and the orientation layer on the metal need to be solidified by high temperature and rub with the friction agent, so the substrate cannot be too thick. In addition, to ensure the LC tuning range, the middle level liquid crystal cell substrate should be as thin as possible.

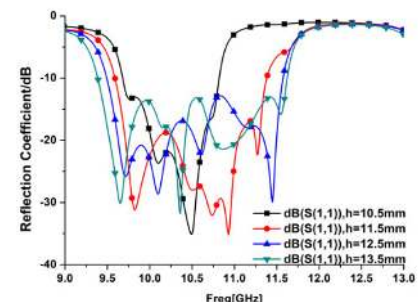
The photographs of the proposed antenna and its measurement are displayed in Fig.6. Considering the existing PCB processing technology, the upper substrate uses Rogers 4350 ($\epsilon_r = 3.66$, $\tan\delta = 0.0012$) substrate which has larger hardness to ensure that the LC cavity will not collapse. The middle substrate uses a Rogers 5880 substrate with a smaller permittivity ($\epsilon_r = 2.2$, $\tan\delta = 0.0009$), so that the 50Ω



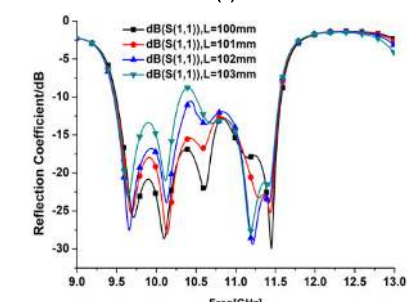
(a)



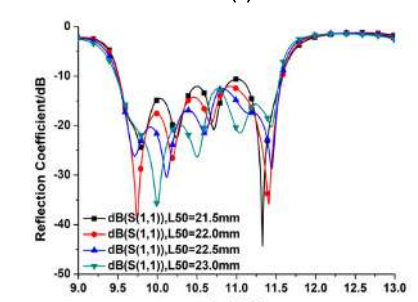
(b)



(c)

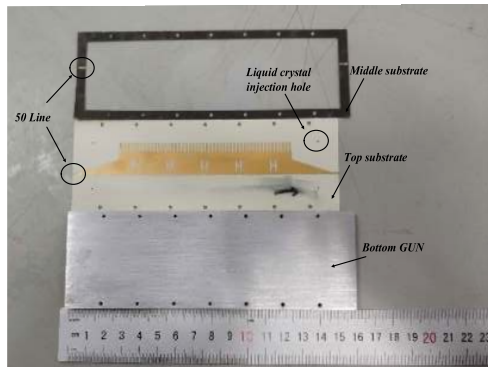


(d)



(e)

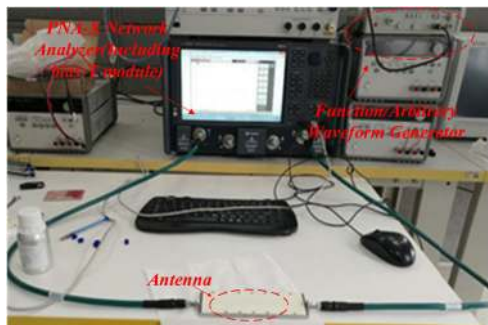
FIGURE 5. Influence of H-slot size change for antenna return wave characteristic (a) L_a , (b) L_b , (c) h , (d) L , and (e) L_{50} .



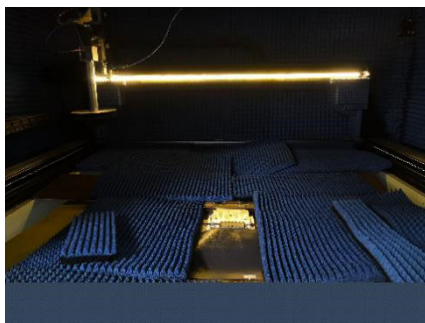
(a)



(b)



(c)



(d)

FIGURE 6. Photographs of the proposed antenna (a) Before assembly, (b) After assembly, (c) S-parameter measurement platform, and (d) directional measurement platform.

feeder is wider to weld the SMA connector. The thickness for both the top and the middle substrate are 0.254mm. The 50Ω feeder line of the top substrate is fitted with the feeder of the middle substrate.

Fig. 7 shows the results of S parameter simulated and measured with 0V bias when loading LC. The measure used

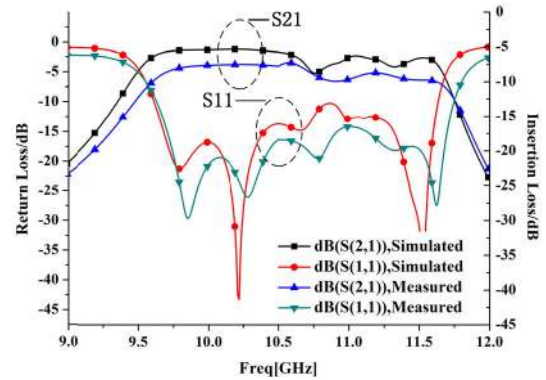


FIGURE 7. Comparison of S-parameter simulation and test results of liquid crystal in initial state.

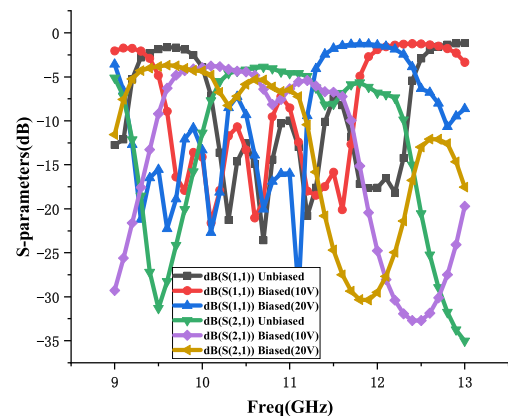


FIGURE 8. Test results of antenna S parameters tuned with liquid crystal.

model AY71-007 LC ($\epsilon_{\perp} = 2.3, \epsilon_{\parallel} = 2.9$ at X band). Because the inhomogeneity of the liquid crystal in the large area of the circuit, the insertion loss of the measure is large.

A. RADIATION PATTERN IN PATTERN RECONFIGURATION

By tuning the equivalent permittivity of the liquid crystal, the unbiased and biased S parameters are shown in Fig.8. Because the passband frequencies change correspondingly due to the tuning of the liquid crystal, the maximum direction deflection band achieved by the antenna is smaller than the antenna passband. The antenna pattern other than the tag will cause distortion caused by the impedance mismatch in tuning the LC. The relative reconfigurable bandwidth is 9.3% (10.2GHz~11.2GHz).

For simplicity, this paper takes the 11GHz test pattern as a reference. The normalized E plane patterns of the antenna before and after bias are shown in Fig.9. By adding bias voltage to the RF port, the direction of the main lobe of the antenna is deflected by 25 degrees. In addition, the pattern and gain of the antenna did not deteriorate significantly during the LC tuning process and the antenna operates in X band with a maximum gain of 10dBi. The results show that the maximum range reconfiguration of the antenna pattern is achieved in the previously described area.

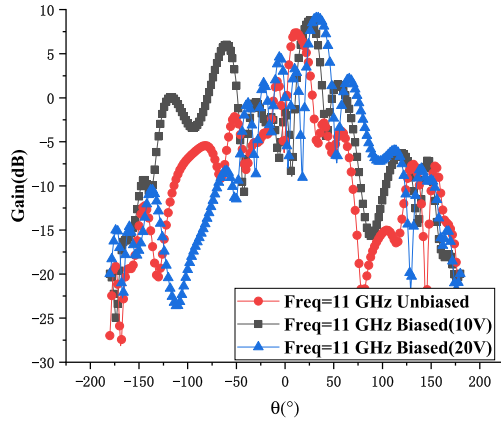


FIGURE 9. Reconfiguration results of pattern at 11GHz.

B. RADIATION PATTERN IN FREQUENCY RECONFIGURATION

Unlike pattern reconfiguration, frequency reconfiguration can be achieved within the whole antenna bandwidth. Since a broadband antenna is designed, for convenience, we revised the representation of antenna pattern and gave the pattern between the unbiased and biased beam-steering at 10 GHz, 10.5 GHz, 11.5 GHz and 12 GHz respectively. Fig.10 shows the pattern deflection at different frequencies and the frequency reconfiguration of LC tuning is realized. The slight pattern difference is due to the impedance mismatch and the change of electric length caused by the change of permittivity and also the measure environment.

C. COMPARISON WITH OTHER ANTENNAS

In recent years, many studies have been carried out on reconfigurable antennas based on liquid crystal materials [9]–[11]. Liquid crystal materials can be tuned in microstrip patches, phase shifters and reflection arrays. There are many leaky wave antennas loaded with liquid crystal materials, mainly because liquid crystal fluidity can be easily integrated into leaky wave antenna, and one-dimensional linear array is more convenient to design liquid crystal bias circuit.

By comparing the different structure antennas in Table 1, it is seen that the scanning angles and gains of the eighth mode substrate integrated circular cavity (EMSICC), the SIW and defected ground structure (DGS) antennas are higher than those of the HMCSIW antenna [12]–[14], only LC material can achieve dynamic tuning. Compared with different types of leaky-wave antennas based on liquid crystal materials [15], the HMCSIW structure proposed in this paper is smaller and conforms to the miniaturization design of antenna.

Although the performance parameters of these leaky wave antennas without tuning technology are better than the LC tunable leaky wave antenna, they can only be applied to a certain type of scene. The LC materials are cheaper and can be tuned by an external bias voltage. Moreover, the LC

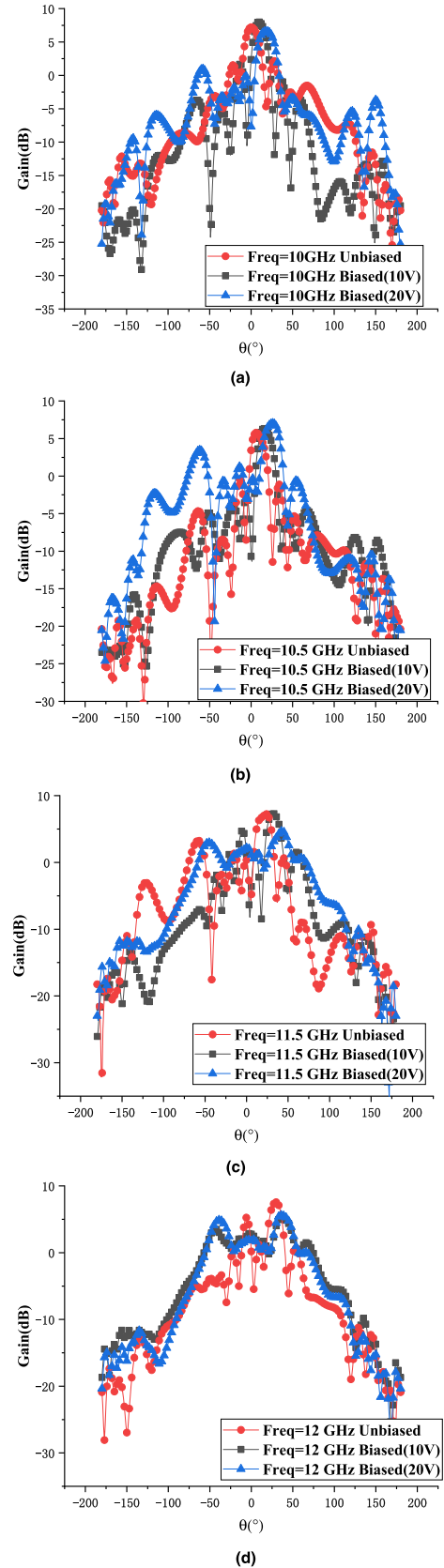


FIGURE 10. Comparison of pattern tuning at different frequencies (a) 10GHz, (b) 10.5GHz, (c) 11.5GHz, and (d) 12GHz.

TABLE 1. Comparison with other antennas.

		Design	Center frequency	Scanning range	Maximum gain	Cavity dimensions	Tunable or not?
LC antennas	[10]	Patch	3.2GHz	-	-	50×50 mm ²	Yes
	[11]	Phased array	10GHz	60°	5.4dB	-	Yes
	[12]	Reflect-arrays	12GHz	90	-	-	Yes
leaky wave antennas	[13]	DGS	12GHz	74°	11dBi	-	No
	[14]	SIW	12GHz	73°	12 dB	211×222 mm ²	No
	[15]	EMSICC	9.4GHz	45°	11dBi	120×9.5 mm ²	No
	[16]	LC	12GHz	36°	8.1dB	90×30 mm ²	Yes
	This work	LC	11GHz	25°	10 dBi	150×12.5 mm ²	Yes

based leaky wave antenna can realize the reconstruction of frequency, pattern and even polarization characteristics.

IV. CONCLUSION

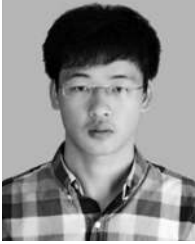
A wideband HMCSIW slot antenna with both pattern and frequency reconfigurability was designed with liquid crystal materials for X band antenna. The waveguide theory is applied to the liquid crystal tuning circuit by unequal potential CSIW structure and miniaturized by half mode processing. Moreover, the antenna achieves broadband radiation by etching the H-slot on the CSIW structure. By adding a bias voltage to tune LC at RF port, the main lobe of the antenna is deflected by 25 degrees and the passband frequency shift is 1 GHz. The antenna efficiency is 26%. Moreover, other indicators are well preserved before and after reconfiguration. The maximum bias voltage is 20V, the maximum gain is 10dBi, and the gain fluctuation is less than 3dB during the tuning. With the tuning of liquid crystal, that is, the equivalent dielectric constant increases, the main lobe of the antenna deflects to 90 degrees. This means that the antenna changes from side-firing mode to end-firing mode, which is consistent with the conclusion that the dispersion characteristics of the upper H-slot change from fast wave to slow wave. Limited by the tuning range of liquid crystal, the pattern deflection of antenna cannot achieve the conversion from side-to-end shooting. The simulated results are well consistent with the measured results, which verify the potential of LC materials for microwave antennas.

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DI JIANG received the M.S. and Ph.D. degrees in electromagnetic field and microwave technology from the University of Electronic Science and Technology of China (UESTC), Chengdu, China, where he has been an Associate Professor in electromagnetic fields and microwave techniques with the School of Information and Communication Engineering, since 2014. His research interests include high-performance microwave and millimeter-wave reconfigurable devices, and antennas and microwave device modeling. He has applied liquid crystal materials to the design of microwave and millimeter-wave devices.



XIAOYU LI is currently pursuing the M.S. degree with the School of Information and Communication Engineering, University of Electronic Science and Technology of China, Chengdu, China. His research interests include liquid crystal technologies and reconfigurable antenna/arrays.



ZIHAO FU is currently pursuing the M.S. degree with the School of Aeronautics and Astronautics, University of Electronic Science and Technology of China, Chengdu, China. His current research interests include tunable RF and microwave passive circuits research, and pattern-reconfigurable antennas analysis and design.



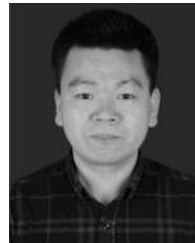
PUHANG RAN is currently pursuing the M.S. degree with the School of Information and Communication Engineering, University of Electronic Science and Technology of China, Chengdu, China. His current research interests include liquid crystal technologies and frequency selective surface analysis and design.



GUOFU WANG was born in Pingdingshan, China, in 1977. He received the M.S. and Ph.D. degrees in signal and information processing from the Chinese Academy of Sciences, in 2005 and 2007, respectively. Since 2017, he has been a Professor with the School of Electrical and Information Engineering, Guangxi University of Technology. His main research interests include adaptive signal processing and image processing. He has a rich research experience in the development of key technologies of photoelectric countermeasure turntables.



ZHI ZHENG (M'11) received the M.S. and Ph.D. degrees in electronic engineering and information or communication engineering from the University of Electronic Science and Technology of China (UESTC), Chengdu, China, in 2007 and 2011, respectively. From 2014 to 2015, he was an Academic Visitor with the Department of Electrical and Electronic Engineering, Imperial College London, U.K. Since 2011, he has been with the School of Information and Communication Engineering, UESTC, where he is currently an Associate Professor. His research interests include the areas of statistical and array signal processing, including direction finding, source localization, target tracking, sparse array design, robust adaptive beamforming, jammer suppression, compressive sensing, machine learning, and convex optimization, with applications to radars, sonar, satellite navigation, wireless communications, and wireless sensor networks.



TIANLIANG ZHANG (M'12) was born in August 1976. He received the M.S. and Ph.D. degrees in physical electronics from the University of Electronic Science and Technology of China (UESTC), Chengdu, China, in 2004 and 2009, respectively, where he is currently a full-time Professor. His research interests include microwave theory and technology, and microwave and millimeter-wave circuits and systems.



WEN-QIN WANG (M'08–SM'16) received the B.S. degree in electrical engineering from Shandong University, Shandong, China, in 2002, and the M.E. and Ph.D. degrees in information and communication engineering from the University of Electronic Science and Technology of China (UESTC), Chengdu, China, in 2005 and 2010, respectively. From 2005 to 2007, he was with the National Key Laboratory of Microwave Imaging Technology, Chinese Academy of Sciences, Beijing, China. Since 2007, he has been with the School of Communication and Information Engineering, UESTC, where he is currently a Professor. From 2011 to 2012, he was a Visiting Scholar with the Stevens Institute of Technology, NJ, USA. From 2012 to 2013, he was a Hong Kong Scholar with the City University of Hong Kong, Hong Kong. From 2014 to 2016, he was a Marie Curie Fellow of Imperial College London, U.K. He has authored two books published by Springer and CRC Press. His research interests include the areas of array signal processing and its applications in radars, communications, and electronic warfare. He was a recipient of the Marie Curie International Incoming Fellowship, the National Young Top-Notch Talent of the Ten-Thousand Talent Program Award, and the Hong Kong Scholar Fellowship. He is an Editorial Board Member of four international journals.

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