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Design of An Absorptive Fabry-Perot Polarizer and Its Application

Peng Mei, *Student Member, IEEE*, Shuai Zhang, *Senior Member, IEEE*, Xian Qi Lin, *Senior Member, IEEE*, and Gert Frølund Pedersen, *Senior Member, IEEE*

Abstract—This letter presents an absorptive Fabry-Perot polarizer and its application on the antenna for gain enhancement and cross-polarization level reduction. The proposed polarizer is designed to achieve a partial reflectance/transmission and an electromagnetic (EM) wave absorptivity more than 90% over 4.5 to 7.5 GHz in horizontal and vertical polarization, respectively. Equivalent circuits of the proposed polarizer are established to explicitly analyze the performance of the proposed polarizer. A rectangular patch antenna operating at 5.8 GHz, as the source antenna, is rigorously assembled with the polarizer. The simulated results, compared to the source antenna, demonstrate significant gain enhancement (around 8dB) and cross-polarization level reduction (more than 10 dB), which is experimentally verified by the measured results.

Index Terms—Fabry-Perot polarizer, equivalent circuit, absorptive, gain enhancement, cross-polarization level reduction.

I. INTRODUCTION

FABRY-PEROT (F-P) cavity antenna has been widely investigated in recent years [1]–[8], as they provide an easy technique to realize a high gain. Typically, it is formed by a partially reflective surface (PRS) and a source antenna, where the PRS is placed above the source antenna with a certain separation. Among the designs, the pattern of the PRS unit is usually highly symmetrical, if this type PRS is employed with a linearly-polarized source antenna, it can be predicted that the cross-polarization of the source antenna is also augmented as the EM in cross-polarization component will also produce multiple reflections between the PRS and the metal ground, resulting in electric fields superposition at the aperture of the PRS. In wireless communication, however, the low cross-polarization level of an antenna is preferred to eliminate the signal interferences. If the cross-polarization EM component can be absorbed by the PRS at the same time, a high gain and

low cross-polarization antenna are expected. Inspired from the absorptive polarizers in visible light frequency band [9], [10], an absorptive polarizer in microwave frequency band is expected to be realized with some lumped lossy elements (such as a lumped resistor).

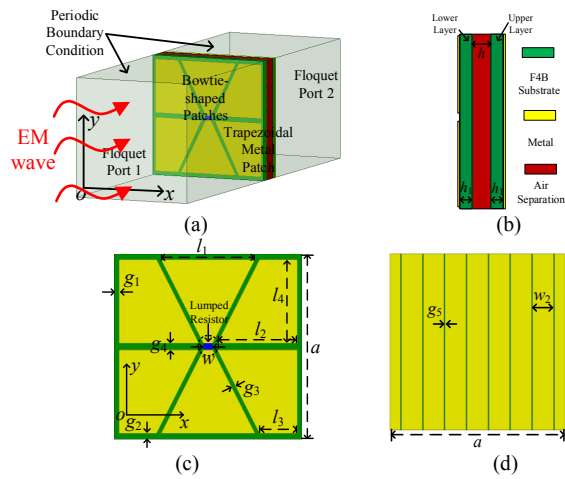


Fig. 1. Geometries of the proposed polarization-discrimination superstrate unit. (a) Perspective view. (b) Side view. (c) Front view of lower layer. (d) Front view of upper layer. ($a=16\text{mm}$, $l_1=8\text{mm}$, $l_2=6.8\text{mm}$, $l_3=3.2\text{mm}$, $l_4=7.2\text{mm}$, $g_1=0.4\text{mm}$, $g_2=0.5\text{mm}$, $g_3=0.4\text{mm}$, $g_4=0.6\text{mm}$, $w=0.8\text{mm}$, $g_5=0.1\text{mm}$, $w_2=1.9\text{mm}$, $h_1=1\text{mm}$, $h=2\text{mm}$, x - and y -direction mean horizontal and vertical polarization, respectively for simple description).

In this letter, an absorptive Fabry-Perot polarizer is proposed. It should be noted that the proposed polarizer is not an actual polarizer defined in physics that a polarizer is an optical filter that lets light waves of a specific polarization pass through while blocking light waves of other polarizations. The proposed polarizer can achieve a partial reflectance/ transmission and an EM absorption performance in horizontal and vertical polarization, respectively. Therefore, two terms of absorptive, and Fabry-Perot are imposed to make the proposed polarizer distinguished with the conventional polarizer. When the proposed polarizer is reasonably placed above a source antenna, where the co-polarized EM wave is partially reflected/ transmitted, while the cross-polarized EM wave radiated from the source antenna is absolutely absorbed by the proposed polarizer, a high gain and low cross-polarization antenna can be predicted compared to the counterparts of the source antenna. For proof of the concept, an absorptive Fabry-Perot polarizer is designed with the capabilities of partial reflectance/ transmission in horizontal polarization, and an EM wave absorptivity over 4.5 to 7.5 GHz by loading lumped resistors in

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vertical polarization. A rectangular patch antenna operating at 5.8 GHz, as the source antenna, is rigorously assembled with the proposed polarizer. The simulated results show a significant gain enhancement and cross-polarization reduction compared to the counterparts of the source antenna at 5.8 GHz, respectively.

II. FABRY-PEROT POLARIZER DESIGN AND ANALYSIS

A. Absorptive Fabry-Perot polarizer unit

Fig. 1 presents the geometries of the proposed polarizer unit. It consists of a lower layer, an air separation, and an upper layer. The lower layer is constructed by a bowtie-shaped and trapezoidal metal patches etched on the supporting substrate. An optimal 120 Ω lumped resistor with packaging of 0.6 mm in length and 0.8 mm in width is soldered in the middle of the bowtie-shaped patches to achieve a wide absorption bandwidth. The upper layer is composed of a rectangular metal array printed on the other supporting substrate. Periodic boundary condition is imposed on the proposed polarizer unit in High-Frequency Structure Simulator (HFSS) to simulate its performance. The supporting dielectric substrates are F4B with a relative permittivity of 2.5, and a loss tangent of 0.002.

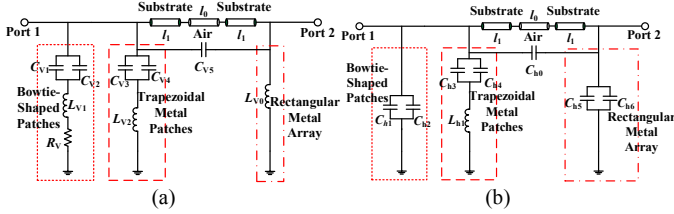


Fig. 2. Equivalent circuits extracted from the proposed polarizer. (a). In vertical polarization. ($C_{v1}=0.175\text{pF}$, $C_{v2}=0.13125\text{pF}$, $C_{v3}=0.066\text{pF}$, $C_{v4}=0.0495\text{pF}$, $C_{v5}=0.008\text{pF}$, $L_{v0}=0.001\text{nH}$, $L_{v1}=3.2\text{nH}$, $L_{v2}=0.1\text{nH}$, $R_v=350\text{ohms}$). (b). In horizontal polarization. ($C_{h1}=0.0165\text{pF}$, $C_{h2}=0.012375\text{pF}$, $C_{h3}=0.0465\text{pF}$, $C_{h4}=0.034875\text{pF}$, $C_{h5}=0.034\text{pF}$, $C_{h6}=0.0255\text{pF}$, $C_{h0}=0.01\text{pF}$, $L_{h1}=0.1\text{nH}$)

First of all, the equivalent circuits of the proposed polarizer unit are all established in vertical and horizontal polarizations as presented in Fig. 2. Every part (bowtie-shaped patches, trapezoidal metal patches, rectangular metal array) in Fig. 1 has its corresponding circuit model as marked with red blocks in Fig. 2. Some pairs of capacitors and inductors (C_{v1} , L_{v1}), (C_{v3} , L_{v2}), L_{v0} , and C_{h1} , (C_{h3} , L_{h1}), C_{h5} represent the equivalent circuit of free-standing bowtie-shaped patches, trapezoidal metal patches, and rectangular metal array, respectively, in vertical and horizontal polarization. Here, a gap of two adjacent metal patches is modeled with a capacitor, and a metal strip is modeled with an inductor. The shunt capacitors C_{v2} , C_{v4} , C_{h2} , C_{h4} , C_{h6} are served as offset values when the effects of the dielectric supporting substrate are considered. C_{v5} and C_{h0} are lower to upper layer capacitors in vertical and horizontal polarization, respectively. The substrate and air separation are modeled with transmission lines with electrical lengths of $l_0 = 2\pi fh/c$ and $l_1 = 2\pi f\sqrt{\epsilon_r}h_1/c$, respectively. h and h_1 are the thickness of air separation and supporting substrate. c is the light velocity in the vacuum. ϵ_r is the relative permittivity of the supporting substrate. The $[ABCD]$ matrix of the entire equivalent circuit can be calculated according to the $[ABCD]$

matrix cascading theorem based on the matrix of every part [11]. Further, the S-parameter of the entire equivalent circuit is freely calculated from the $[ABCD]$ matrix accordingly. It is deduced that the proposed polarizer has great potential to achieve an absorptivity in vertical polarization, and a partial reflectance and transmission in horizontal polarization when the appropriate dimensions of the proposed polarizer unit and a proper value of lumped resistor are imposed. Once all dimensions are determined, the values in the equivalent circuit can be deduced according to the approach reported in [12], [13]. For demonstration, we select the dimensions of the proposed polarizer unit as supplied in Fig. 1. Its S-parameter is simulated. Fig. 3 compares the S-parameter of the proposed polarizer under HFSS and equivalent circuit (EQC) simulations. It is observed that a great agreement between them is obtained. The slight discrepancies are due to the ideal circuit model used in the equivalent circuit simulation, of which all the lumped components are considered as lossless elements. Fig. 3 (a) also plots the absorptivity of the proposed polarizer in vertical polarization. It is observed that the absorptive rate is above 90% over the frequency band from 4.5 to 7.5 GHz. Moreover, it is observed in Fig. 3(b) that the proposed polarizer indeed demonstrates a partial reflectance/transmission performance in horizontal polarization. The performance of the proposed polarizer is also evaluated with a sensitive parameter h . From the Fig. 4, it is seen that absorption band is shifting toward higher frequencies when the thickness of air separation h is decreased. When the h is decreased, the input impedance seen from the air separation to the upper layer is also changed accordingly. A small h would make the electric length of the air separation small, leading to a high frequency shifting. The partial transmission and reflectance performance are still maintained with different h .

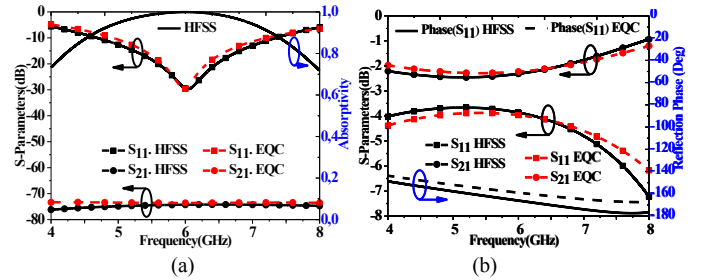


Fig. 3. S-parameters of the proposed polarizer. (a). In vertical polarization. (b). In horizontal polarization.

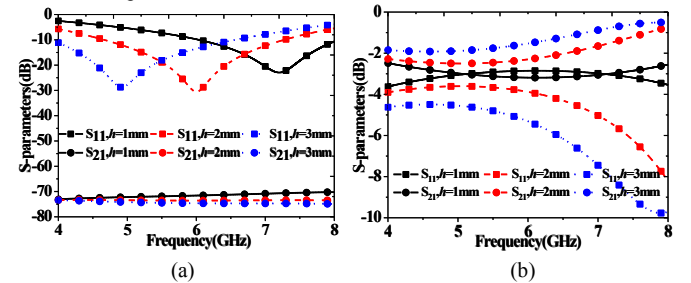


Fig. 4. S-parameters of the proposed polarizer versus h . (a). In vertical polarization. (b). In horizontal polarization.

B. The effects of the trapezoidal metal patches

The effects of trapezoidal metal patches on the performance of the proposed polarizer are investigated. As stated before, the trapezoidal metal patches have their own equivalent circuit model. When they are removed, their corresponding circuit model should also be erased in the equivalent circuit accordingly. Based on the values of circuit elements (C_{h1} , C_{h2} , C_{h3} , C_{h4} , C_{h3} , and C_{h4} are bigger than C_{h1} and C_{h2}) in horizontal polarization, a bigger capacitor means a smaller capacitive reactance, therefore it can be deduced that the S-parameters of the proposed polarizer will be slightly varied when the trapezoidal metal patches are removed, but the partial reflectance/transmission performance is still maintained as shown in Fig. 4 (a). However, by comparing the values of circuit elements (C_{v1} , C_{v2} , C_{v3} , C_{v4} , C_{v3} , and C_{v4} are much smaller than C_{v1} and C_{v2}) in vertical polarization, it can be deduced that the absence of the trapezoidal metal patches makes the reflection coefficient of the proposed polarizer worse as shown in Fig. 5 (a), where it is observed that the absorptivity of the proposed polarizer is greatly damaged, and is only less than 75% from 4.5 to 7.5GHz.

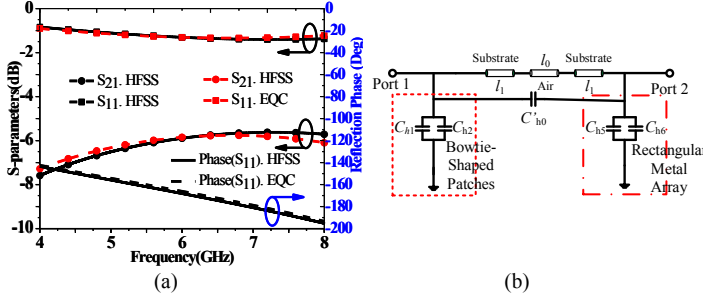


Fig. 4. The proposed polarizer when the trapezoidal metal patches are removed in horizontal polarization. (a). S-parameter. (b). Equivalent circuit.

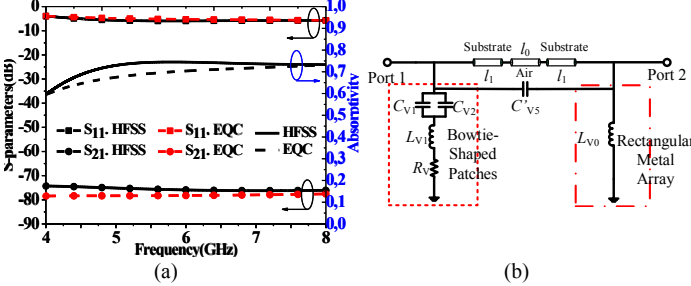


Fig. 5. The proposed polarizer when the trapezoidal metal patches are removed in vertical polarization. (a). S-parameter. (b). Equivalent circuit.

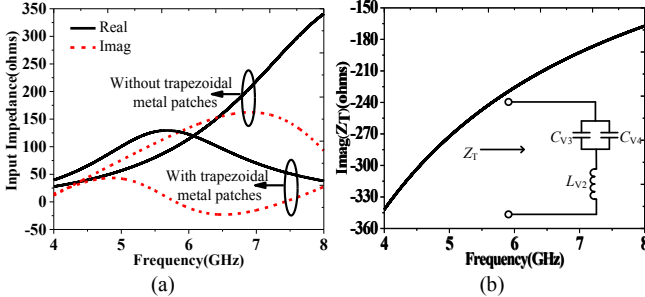


Fig. 6. (a). The input impedance of the proposed polarizer unit with or without the trapezoidal metal patches in vertical polarization. (b). The impedance Z_T of the trapezoidal metal patches.

Alternatively, we can also evaluate the effects of the trapezoidal metal patches by discussing the input impedance. As

described in subsection A, the lumped resistor only works in vertical polarization when the inductive current on the surface of the bowtie-shaped patches flows through it. Therefore, we can regard the lumped resistor as a port whose port impedance is equal to the value of the lumped resistor in simulation as illustrated in [14]. Fig. 6 (a) presents the input impedance of the proposed polarizer with and without the trapezoidal metal patches in vertical polarization. It is observed that the presence of the trapezoidal metal patches not only introduces a capacitive reactance to offset its original inductive reactance but also maintains the real part of the input impedance in the range of 50 to 125 Ω over 4.5 to 7.5 GHz. The result can also be explained by the equivalent circuit: according to the values of C_3 , C_4 , and L_2 , the input impedance of the trapezoidal metal patches indeed shows a strong capacitive reactance from 4.5 to 7.5GHz as shown in Fig. 6(b) that is used to offset the inductive reactance introduced by the structure without the trapezoidal metal patches. Based on the input impedance of the proposed polarizer unit in vertical polarization, a lumped resistor with a proper value can be determined to obtain the optimal bandwidth and absorptivity. In addition, it is found that the trapezoidal metal patches have a function of miniaturization that lower the absorptive frequencies of the proposed polarizer.

III. APPLICATIONS

A. The configuration of the assembled antenna

The proposed polarizer is fully employed on a source antenna to improve its performance. The configurations of the assembled antenna are shown in Fig. 7. Three substrates are separated by two air spacers. Plastic screws are used to keep the substrates parallel and a definite distance with each other. The height H is calculated with $-2H*2\pi f/c + \varphi_{F-P} + \varphi_{ground} = \pm 2n\pi$, ($n=0,1,2, \dots$), where φ_{F-P} is the reflection phase of the proposed polarizer at 5.8 GHz, φ_{ground} is the reflection phase of the metal ground that is usually served as 180 deg.

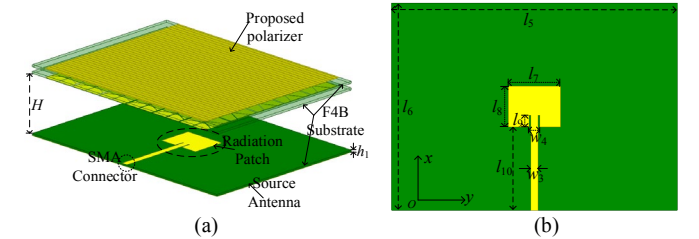


Fig. 7. Geometries of the assembled antenna. (a) Perspective view. (b) Front view of source antenna. ($l_5=110\text{mm}$, $l_6=80\text{mm}$, $l_7=20\text{mm}$, $l_8=15.7\text{mm}$, $l_9=4.6\text{mm}$, $l_{10}=32.15\text{mm}$, $w_3=2.8\text{mm}$, $w_4=4.0\text{mm}$, $h_1=1\text{mm}$, $H=27\text{mm}$)

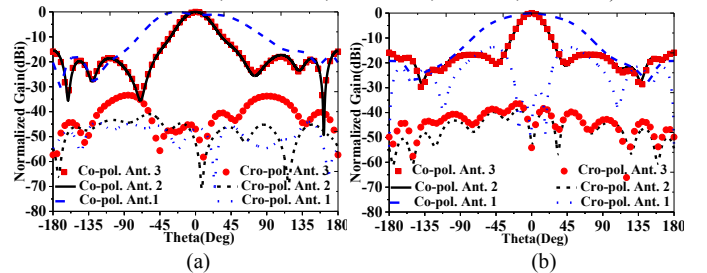


Fig. 8. Comparisons of simulated normalized radiation patterns of the three antennas at 5.8 GHz. (a). E-plane (xoz -plane). (b). H-plane (yoz -plane). (The

normalized radiation patterns are obtained by normalizing the co-polarization and cross-polarization of antennas 1, 2, and 3 to their respective peak gains.)

B. Radiation patterns comparison

In order to demonstrate the performance improvement by employing the proposed polarizer reasonably, three types of antennas are investigated: 1) Ant 1 - the source antenna, 2) Ant 2 - the source antenna assembled with the proposed polarizer, and 3) Ant 3 - the source antenna assembled with the proposed polarizer but all lumped resistors are removed. For brevity, only the radiation patterns of these antennas are simulated and compared at 5.8 GHz. At the frequency, the reflection coefficients are all below -10dB to ensure the work of these antennas.

As shown in Fig. 8, the normalized cross-polarization level of Ant 3 is worse than the counterparts of Ant 1 and Ant 2 at some angle ranges in E-plane; the normalized cross-polarization level of Ant 1 is much worse than the counterparts of Ant 2 and Ant 3 in H-plane. It is therefore concluded that Ant 2 has the optimal cross-polarization performance in both E- and H-plane at 5.8 GHz among them, and the peak gain of the Ant 2 is much higher than that of Ant 1 by judging from the beamwidth of the main beam of Ant 1 and 2.

C. Discussions

It is found that the rectangular metal array in the upper layer can be regarded as a conventional polarizer that would also be employed to reduce the cross-polarization level intuitively. From the simulated results, it is observed that Ant 3 indeed has relatively low cross-polarization levels compared with that of Antenna 1 in E- and H-plane. The phenomena are explained as follows: a conventional polarizer can reflect the EM wave in a certain polarization. In our scenario, the cross-polarized EM wave experiences multiple reflections between the superstrate (lumped resistors are all removed) and metal ground. The cross-polarized EM wave power is consumed by conductor and dielectric losses when these reflections occur. However, the residual cross-polarized EM wave power is still dominated and radiates into the free space via side walls. According to the law of conversation of energy, the radiated residual cross-polarized EM wave power must increase the cross-polarization level at a certain angle or a range of angles in E-plane or H-plane as verified by the radiation pattern of Ant 3 in E-plane.

When the lumped resistor R_v is considered, the superstrate can be served as an absorber that directly absorbs the cross-polarized EM wave radiated from the source antenna. Therefore, almost no cross-polarized EM wave can radiate into the free space via side walls, resulting in a great cross-polarization reduction within the full angle range (-180 to 180 deg). As a result, the proposed polarizer has its unique superiority over a conventional polarizer in terms of cross-polarization level reduction. In addition, if the proposed antenna operates at the range of millimeter-wave or terahertz bands, the lumped resistors are avoidable. A conventional polarizer can be adopted alternatively because the conductor and dielectric losses are sufficient to consume the energy of the cross-polarized EM wave when these multiple reflections occur.

IV. EXPERIMENTAL MEASUREMENT

As shown in Fig. 8, although the cross-polarization level of Ant 3 in E-plane at 5.8GHz is higher than the counterpart of Ant 2, the differences are difficult to be measured and detected during the practical antenna measurement. Therefore, only the reflection coefficients and radiation patterns of Ants 1 and 2 are measured and compared. Fig. 10 (a) presents the measured reflection coefficients of Ants 1 and 2. These two antennas both work well at 5.8 GHz. The boresight realized gains of Ants 1 and 2 are also measured from 5.5 to 6.0 GHz as shown in Fig. 10 (b). It is observed that a significant gain enhancement is obtained. In particular, the measured peak gain of Ant 2 is 14.0 dBi, indicating a gain enhancement of more than 8 dB at 5.8 GHz. According to the measured gain at 5.8 GHz, the aperture efficiency of the proposed antenna is calculated to be 69.86%.

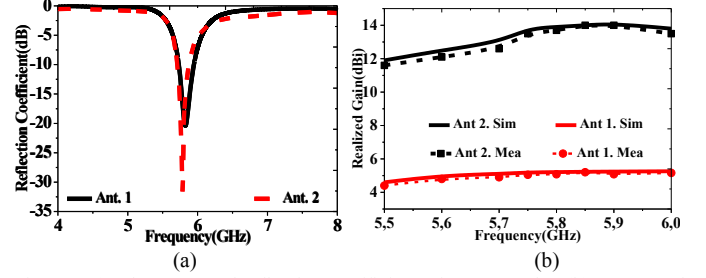


Fig. 10. (a). The measured reflection coefficient of Ants 1 and 2. (b). Measured and simulated realized gain of Ants 1 and 2 over 5.5 to 6.0 GHz.

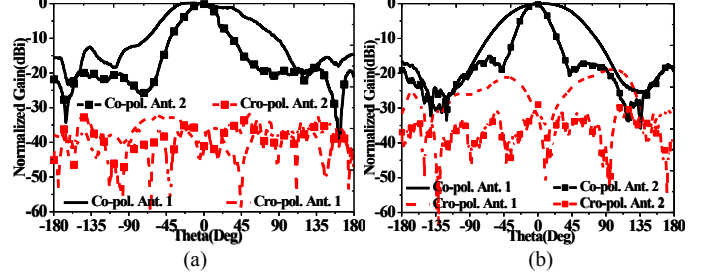


Fig. 11. The measured normalized radiation patterns of Antennas 1 and 2 at 5.8 GHz. (a). E-plane. (b). H-plane.

The normalized radiation patterns of Ants 1 and 2 are also measured in an anechoic chamber. In order to measure the cross-polarization level of Ants 1 and 2 accurately, the under-test and transmitting antennas must be in good alignment. Figs. 11 (a) and (b) compare the measured normalized radiation patterns in E- and H-plane at 5.8 GHz, respectively. It is observed that significant cross-polarization level reduction is obtained in H-plane. The main beam of Ant 2 is much narrower than the counterpart of Ant 1, which shows a good agreement with the simulated results illustrated in Fig. 8.

V. CONCLUSION

In conclusion, an absorptive Fabry-Perot polarizer and its application on the antenna are presented in this letter, respectively. The proposed polarizer is placed above a source antenna with a certain separation to realize a gain enhancement and cross-polarization reduction. The measured results demonstrate a great cross-polarization reduction in H-plane at 5.8GHz and a significant gain enhancement from 5.5 to 6.0 GHz are all observed.

REFERENCES

- [1] P. Qin, L. Ji, S. Chen, and Y. Guo, "Dual-polarized wideband Fabry-Perot antenna with quad-layer partially reflective surface," *IEEE Antennas Wireless Propag. Lett.*, vol. 17, no. 4, pp. 551-554, Apr 2018.
- [2] M. Abdelghani, H. Attia, and T. Denidni, "Dual- and wideband Fabry-Perot resonator antenna for WLAN applications," *IEEE Antennas Wireless Propag. Lett.*, vol. 16, pp. 473-476, 2017.
- [3] K. Konstantinidis, A. Feresidis, and P. Hall, "Dual subwavelength Fabry-Perot cavities for broadband highly directive antennas," *IEEE Antennas Wireless Propag. Lett.*, vol. 13, pp. 1184-1186, 2014.
- [4] H. Attia, M. Abdelghani, and T. Denidni, "Wideband and high-gain millimeter-wave antenna based on FSS Fabry-Perot cavity," *IEEE Trans. Antennas Propag.*, vol. 65, no. 10, pp. 5589-5594, Oct 2017.
- [5] N. Wang, C. Wu, L. Talbi, Q. Zeng, and J. Xu, "Wideband Fabry-Perot resonator antenna with two complementary FSS layers," *IEEE Trans. Antennas Propag.*, vol. 62, no. 5, pp. 2463-2471, May 2014.
- [6] L. Zhou, X. Chen, and X. Duan, "Fabry-Perot resonator antenna with high aperture efficiency using a double-layer nonuniform superstrate," *IEEE Trans. Antennas Propag.*, vol. 66, no. 4, pp. 2061-2066, Apr 2018.
- [7] D. Abbou, T. Vuong, R. Touhami, F. Ferrero, D. Hamzaoui, and M. Yagoub, "High-gain wideband partially reflecting surface antenna for 60 GHz system," *IEEE Antennas Wireless Propag. Lett.*, vol. 16, pp. 2704-2707, 2017.
- [8] K. Konstantinidis, A. Feresidis, and P. Hall, "Multilayer partially reflective surfaces for broadband Fabry-Perot cavity antennas," *IEEE Trans. Antennas Propag.*, vol. 62, no. 7, pp. 3474-3481, Jul 2014.
- [9] J. Lee, Y. Song, J. Lee, J. Ha, K. Hwang, and D. Zang, "Optically bifacial thin-film wire-grid polarizers with nano-patterns of a graded metal-dielectric composite layer," *Opt. Express*, vol. 16, no. 21, 2008.
- [10] M. Suzuki, A. Takada, T. Yamada, T. Hayasaka, K. Sasaki, E. Takahashi, and S. Kumagai, "Low-reflective wire-grid polarizers with absorptive interference overlayers," *Nanotechnology* **21** (2010) 175604.
- [11] D. M. Pozar, *Microwave Engineering*, 4th ed. Hoboken, NJ, USA: Wiley, 2012.
- [12] M. Joozadani, and M. Amirhosseini, "Wideband absorber with combination of plasma and resistive frequency selective surface," *IEEE Trans. Plasma Sci.*, vol. 44, no. 12, pp. 3254-3261, Dec. 2016.
- [13] F. Costa, A. Monorchio, and G. Manara, "Efficient analysis of frequency-selective surfaces by a simple equivalent-circuit model," *IEEE Antennas Propag Magazine*, vol. 54, no. 4, pp. 35-48, 2012.
- [14] X. Lin, P. Mei, P. Zhang, Z. Chen and Y. Fan, "Development of a resistor-loaded ultraband absorber with antenna reciprocity," *IEEE Trans. Antennas Propag.*, vol. 64, no. 11, pp. 4910-4913, Nov. 2016.