Reduction of Mutual Coupling for Broadband Vivaldi Antennas Using Characteristic Modes Analysis and Lumped Loads

Zhenpeng Ma and Qi Wu

School of Electronic and Information Engineering
Beihang University, Beijing, 100191, China
mazhp@buaa.edu.cn, qwu@buaa.edu.cn

Abstract **─** A method to reduce mutual coupling for broadband Vivaldi antennas is presented in this paper. Theory of characteristic modes is used to analyze the surface currents on the Vivaldi antennas which may contribute to mutual coupling, and inductive loads are used to suppress these modes. Mutual coupling between adjacent Vivaldi antennas is reduced by 10~20 dB on average in a wide bandwidth. Three configurations, including the classical design, design with slot, and design with inductive loads are studied. Numerical and experimental results are presented to verify the effectiveness of this method, which ensures that the method has very little influence to normal operation of Vivaldi antennas.

Index Terms **─** Characteristic modes analysis, lumped loads, mutual coupling, Vivaldi antenna.

I. INTRODUCTION

Mutual coupling between antennas has been studied extensively due to the widespread use of multi-antenna system, such as the multiple input multiple output systems, modern vehicles and antenna systems on aircraft. Strong mutual coupling may result in performance degradation of wireless systems. The method to reduce mutual coupling in these systems is limited by a number of factors. For example, for airborne antenna system, the distance between antennas is under restrictions of the space, so it is unrealistic to reduce mutual coupling by increasing the distance between antennas. Therefore, it is necessary to find a method to analyze mutual coupling and mitigate it with little influence to the normal operation of antennas.

Theory of characteristic modes was proposed in 1960s [1, 2], and this theory is found to be effective to analyze and reduce mutual coupling of antennas [3, 4]. Surface currents on the antenna can be separated into several modes, and the contributions of each mode to mutual coupling are evaluated through modal mutual admittance [3]. Lumped loads can be used to suppress specific modes which contribute to mutual coupling, so that the mutual coupling will be reduced with little influence to normal operation of antennas.

Vivaldi antenna is a kind of broadband antenna, which can be designed to cover the frequency range from 500 MHz to 7 GHz [5, 6]. Vivaldi antenna is practical because it has simple construction, wide band-width and relatively high gain [7]. It can be used in the array form for enhanced performance and functionality. Therefore, Vivaldi antenna has been widely used in radar and other wireless systems. However, in a shared aperture, the mutual coupling between antennas tends to be strong and is possible to affect the normal work of the antenna array. So it deserves consideration that how to reduce mutual coupling in wide frequency band.

Although there are a few works for the reduction of mutual coupling between antennas based on the theory of characteristic modes, they usually consider only a few frequency points, i.e., in a relatively narrow band. The method presented in this paper, on the other hand, analyzes the mode current at different frequency points, and then find the critical places where the eigencurrents have large contribution to mutual coupling. And based on this analysis, the reduction of mutual coupling for Vivaldi antennas on the broadband is realized.

The remaining parts of this paper are organized as follows. In Section II, theory of characteristic modes is introduced and modal mutual admittance for Vivaldi antennas is analyzed. In Section III, characteristic mode analysis (CMA) for Vivaldi antennas is shown, and a method is proposed to reduce mutual coupling in a wide bandwidth. Some numerical and experimental results are presented in Section IV. Short conclusions are discussed in Section V.

II. CMA OF MUTUAL COUPLING FOR VIVALDI ANTENNAS

A. The theory of characteristic modes

According to the theory of characteristic modes, surface currents on a conducting body can be decomposed into infinite number of current modes by the eigenvalue equation:

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$$X[\mathbf{J}_n] = \lambda_n R[\mathbf{J}_n]\,, \tag{1}$$

where *X*, *R* are the imaginary and real parts of operator *Z* respectively. The operator *Z* is linear and symmetric and can be obtained from the electric field integral equation (EFIE), which can be written as [8]:

$$-\mathbf{E}^i_{\tan} = (-\,\mathrm{j}\omega\mathbf{A} - \nabla\Phi)_{\tan}\,, \tag{2}$$

with the vector magnetic potential defined as:

$$\mathbf{A}(\mathbf{r}) = \frac{\mu}{4\pi}\int_S \mathbf{J}\frac{e^{-jk\mathbf{R}}}{\mathbf{R}}dS'\,, \tag{3}$$

and the scalar electric potential as:

$$\Phi(\mathbf{r}) = \frac{1}{4\pi\varepsilon}\int_S \sigma\frac{e^{-jk\mathbf{R}}}{\mathbf{R}}dS'\,. \tag{4}$$

The operator *Z* can be written from EFIE as:

$$\mathbf{Z}(\mathbf{J}) = [\mathrm{j}\omega\mathbf{A}(\mathbf{J}) + \nabla\Phi(\mathbf{J})]_{\tan}\,. \tag{5}$$

Using the method of moment (MOM) and Rao-Wilton-Glisson (RWG) basis functions, eigenvalue λ_n and eigencurrent $\mathbf{J}_n$ can be solved from (1). From the theory of eigenvalue equation, it can be proved that $\mathbf{J}_n$ is orthogonal on the conducting body surface.

Surface currents on the conducting body under a specified excitation can be decomposed as:

$$\mathbf{J} = \sum_n \alpha_n \mathbf{J}_n\,, \tag{6}$$

where α_n is modal weighting coefficient. By substituting (6) into (1) and using the orthogonal property of $\mathbf{J}_n$, α_n can be rewritten as:

$$\alpha_n = \frac{\langle \mathbf{E}^i_{\tan}, \mathbf{J}_n\rangle}{(1+\mathrm{j}\lambda_n)}\,. \tag{7}$$

From (6) and (7), the surface currents on the conducting body can be represented by a linear superposition of weighted eigencurrents. Recent researches show that eigencurrents have interesting physical insights and different eigencurrents have different contributions to mutual coupling. Mutual coupling can be reduced by suppressing the eigencurrents that contribute to mutual coupling much. Hence, it deserves a consideration that how to evaluate the contribution to mutual coupling from a certain eigencurrent.

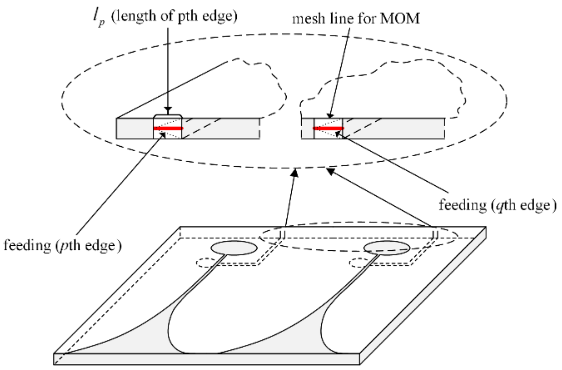


Fig. 1. Illustration of the structure of Vivaldi antennas.

B. Modal mutual admittance for Vivaldi antennas

Modal mutual admittance for general antenna pairs is discussed in [3], which represents the contribution of each mode to the mutual coupling. For Vivaldi antennas, its modal mutual admittance is computed by a similar approach.

Structure of Vivaldi antennas discussed in this paper is shown as Fig. 1. The electromagnetic wave is radiated from the slot line and the antennas are fed by a microstrip line. In order to compute the characteristic modes, the antennas are meshed into a series of triangles using RWG basis functions. Antenna 1 is fed by the port located at the *p*th edge with length l_p, and antenna 2 is fed by the port located at the *q*th edge with length l_q. The mutual admittance between antenna 1 and antenna 2 can be expressed as:

$$Y_{21} = \sum_{n=1}^{\infty}\frac{I_n(p)I_n(q)l_pl_q}{1+j\lambda_n}\,, \tag{8}$$

where $I_n(p)$ and $I_n(q)$ are the nth order eigencurrents at the *p*th and *q*th edge, and λ_n is the nth order of eigenvalue. From (8), the modal mutual admittance can be written as:

$$Y_{21}^n = \frac{I_n(p)I_n(q)l_pl_q}{1+j\lambda_n}\,. \tag{9}$$

From (9), the contribution to mutual coupling of each mode can be evaluated at separated frequency points. Taking account of wide bandwidth of Vivaldi antennas, modal mutual admittance at several frequency points need to be considered. Therefore, the eigencurrents contributed to mutual coupling much at different frequency points need to be suppressed. In order to suppressed a certain mode, lumped loads such as inductive loads usually are used [8]. The position of lumped loads can be obtained from CMA.

III. A REDUCTION OF MUTUAL COUPLING FOR VIVALDI ANTENNAS USING CMA

The size and structure of Vivaldi antennas discussed in this paper is shown as Fig. 2. The size of one Vivaldi element is 140 mm × 220 mm × 0.8 mm. Relative permittivity of the dielectric substrate is 2.65. The bandwidth of Vivaldi element is from 1 GHz to 3 GHz. The antenna is fed by microstrip line with a width of 2.2 mm, which is also the length of the *p*th and *q*th edge. Two Vivaldi elements are placed side by side and the mutual coupling between the two antennas is strong. It can be noticed from the structure that, possibly mutual coupling is mainly caused more from the ground plane, rather than from the space. Therefore, analyzing the eigencurrents on the ground plane will be efficient.

To find out the eigencurrents which contribute mainly to the mutual coupling, the modal mutual admittance at several frequent points is calculated from (9) and is shown in Table 1. It can be noticed from Table 1 that the modal mutual admittance of different modes has similar order of magnitudes, which means that they have similar contributions to mutual coupling. Hence, it is necessary to observe several eigencurrents in order to find out how to suppress eigencurrents effectively. The eigencurrents with large modal mutual admittance at 1.12 GHz is shown in Fig. 3.

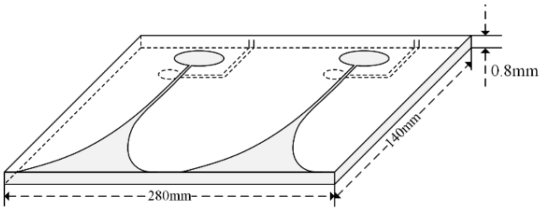


Fig. 2. Illustration of the size and structure of Vivaldi antennas.

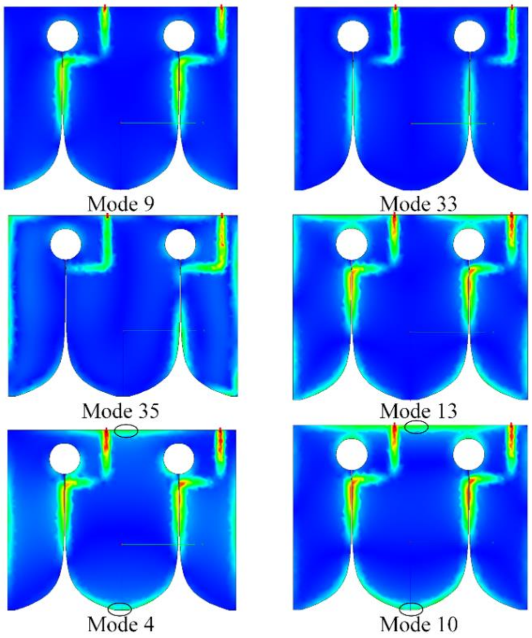

Mode 9
Mode 33
Mode 35
Mode 13
Mode 4
Mode 10

Fig. 3. Distributions of eigencurrents with relatively large modal mutual admittance.

From Fig. 3, it can be observed that these eigencurrents have similar distributions in the tapered slot area of Vivaldi antennas. Because the normal work condition of antennas needs to be guaranteed, it needs to be noticed that the current in the work area has better not been affected. From the current distributions of modes 4 and 10, the edges between the two antennas, which are shown by ellipses in Fig. 3, are likely to need attention. Although modes 4 and 10 don't have largest modal mutual admittance, they have the same order of magnitudes as the largest one. In addition, the modes which have the largest modal mutual admittance, such as modes 9 and 33 only have current distributions in the place of work area. It is difficult to deal with these modes. Therefore, it is significant to analyze these modes like modes 4 and 10. By analyzing eigencurrents at other frequency points, which is shown in Fig. 4, the place that is marked tends to be significant to mutual coupling. We can control the current on such place to suppress corresponding eigencurrent, and then, the mutual coupling will be mitigated.

From the research in [3, 4], lumped loads such as inductive loads are usually utilized to suppress eigencurrent. For Vivaldi antennas, inductive loads might be a choice. However, because the surface current tends to choose the path with lower impedance, only inductive may be not effective enough. A slot between the two antennas is necessary [3].

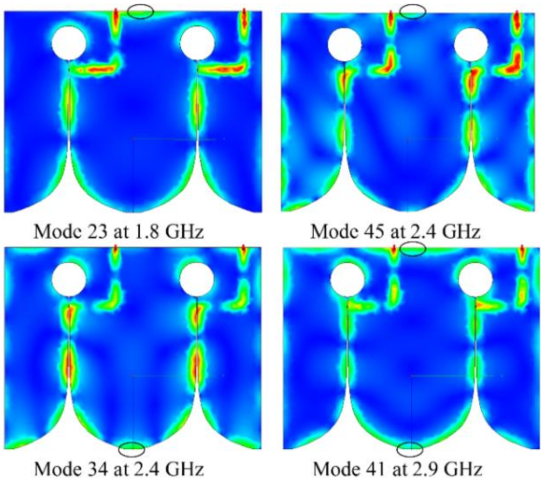

Mode 23 at 1.8 GHz
Mode 45 at 2.4 GHz
Mode 34 at 2.4 GHz
Mode 41 at 2.9 GHz

Fig. 4. Eigencurrents with similar current distributions at other frequencies considered.

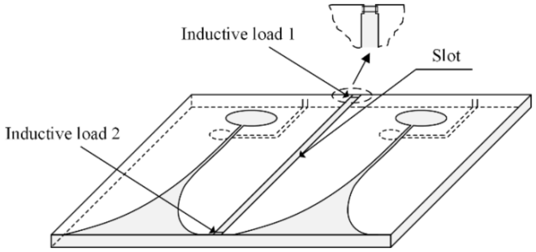


Fig. 5. Illustration of optimized antenna with slot and inductive loads.

Table 1: MMA of two Vivaldi antennas

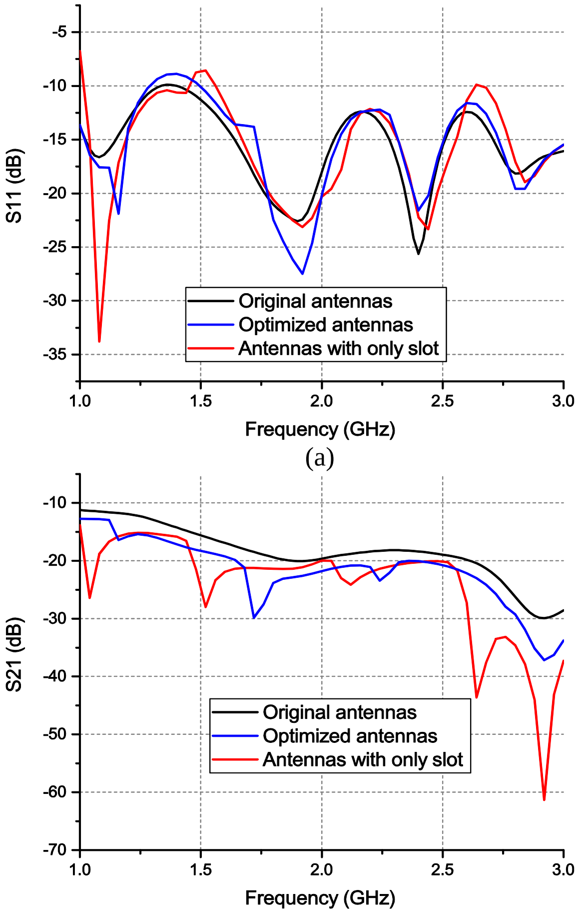
1.12 GHz	Mode 9	Mode 33	Mode 35	Mode 13	Mode 4	Mode 10
	6.87e-3	4.32e-3	3.42e-3	2.79e-3	2.58e-3	1.88e-3
1.8 GHz	Mode 41	Mode 23	Mode 29	Mode 10	Mode 36	Mode 17
	4.36e-3	3.91e-3	3.39e-3	3.04e-3	2.21e-3	2.15e-3
2.4 GHz	Mode 45	Mode 28	Mode 13	Mode 19	Mode 34	Mode 32
	1.95e-3	1.52e-3	1.44e-3	1.44e-3	1.28e-3	1.28e-3
2.9 GHz	Mode 50	Mode 49	Mode 36	Mode 31	Mode 24	Mode 41
	3.73e-3	2.93e-3	2.26e-3	1.73e-3	7.29e-4	4.47e-4

The adopted plan is shown in Fig. 5. A slot is cut out between the two antennas. On the two edges of the slot, two inductive loads are placed respectively. In this way, the eigencurrents at different frequency points will be suppressed on these places, so that the mutual coupling should be reduced in the wide work band.

IV. NUMERICAL SIMULATION AND EXPERIMENTAL VERIFICATION

A. Numerical simulation for Vivaldi antennas

To verify the effectiveness, numerical simulation is completed by HFSS. It can be noticed that the slot between the two antennas will also contribute to the reduction of mutual coupling, hence it is necessary to compare results of antennas with only slot and antennas with slot and inductive loads. The value of the two inductive loads are confirmed as 2.3 nH for load 1 and 10.8 nH for load 2, by parametric scanning to get a relatively better performance for mutual coupling. The results of S-parameter are shown in Fig. 6, and the radiation patterns at 1.12 GHz and 2.4 GHz are shown in Fig. 7 respectively.

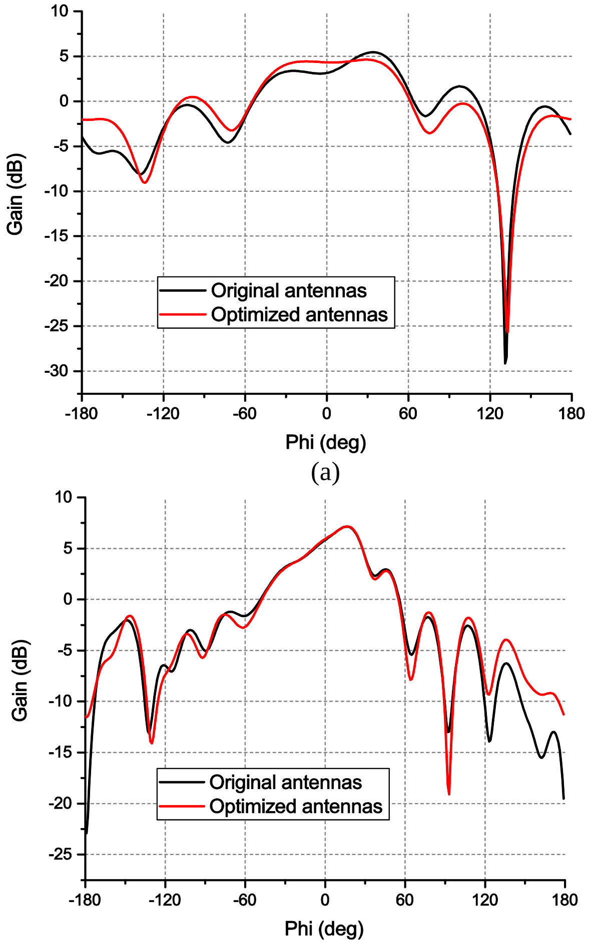


(a)

(b)

Fig. 6. S-parameters of the 3 kinds of Vivaldi antennas: (a) S11 and (b) S21.

As shown in Fig. 6 (a), for S11, there is no significant difference among the three antennas, which means that the normal work condition is not changed a lot. The S21 parameter of the optimized one with inductive loads is reduced in the whole work band of Vivaldi antennas. It can be observed that the mutual coupling at 2.7 GHz is reduced by about 30 dB. Furthermore, the mutual coupling from 1 GHz to 3 GHz is lower than -15 dB. Compared to the antennas with only slot, which is shown in blue lines in Fig. 6 (b), it can be observed that the optimized antennas with loads perform better, especially in the high frequency band.



(a)

(b)

Fig. 7. Radiation pattern of Vivaldi antennas at: (a) 1.12 GHz and (b) 2.4 GHz.

This illustrates that the inductive loads indeed play a role in reducing mutual coupling.

From Fig. 7, it can be noticed that the symmetry of the radiation pattern is better after optimizing, mainly due to the reduction of the mutual coupling at 1.12 GHz. This is a good result because this means that the radiation characteristic of antennas is easier to predict and will improve the performance of the Vivaldi array. At 2.4

GHz, the mutual coupling of antennas is reduced by only 2 dB, and the radiation patterns of original and optimized antenna array are similar. This is result from the similar work mode currents, which are hardly influenced by the inductive loads.

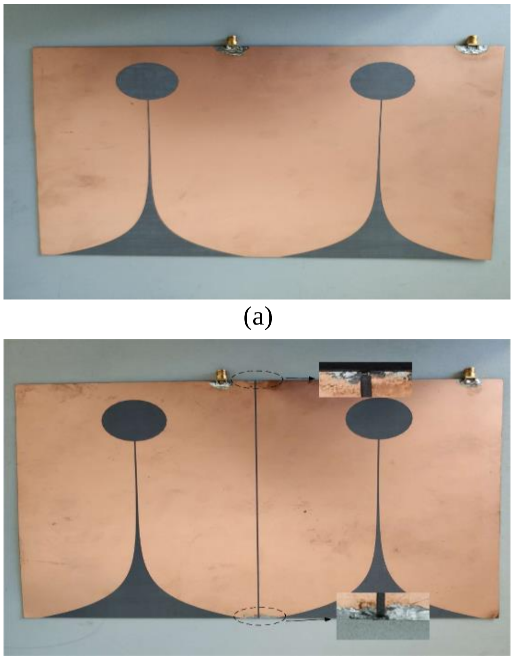
B. Experiment verification

In order to verify the simulation, the Vivaldi antennas are fabricated and measured. The photographs of original and optimized antennas are shown in Fig. 8, and the result of experiment is shown in Fig. 9.

From Figs. 9 (a) and (b), it can be noticed that the S-parameters agree well between measured and simulated. As shown in Fig. 9 (c), the mutual coupling is reduced by 20 dB at most at about 1.6 GHz, and the mutual coupling is bellower than -15 dB almost in the whole work band.

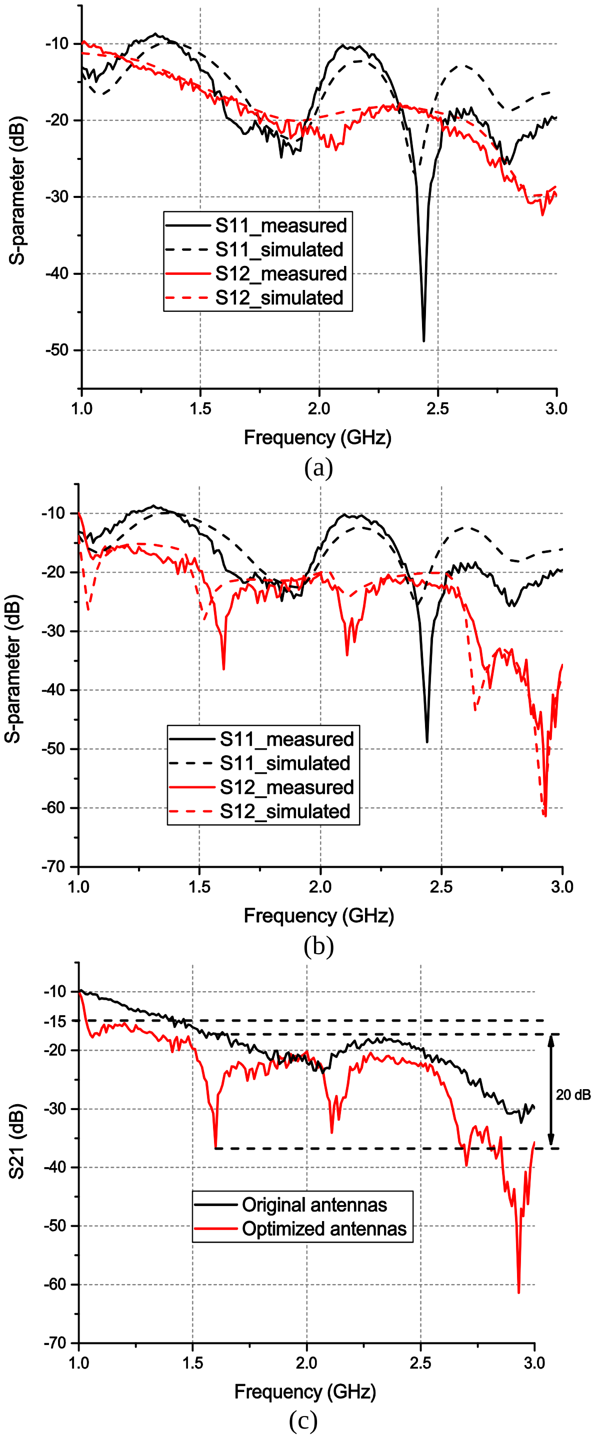
V. CONCLUSION

In this paper, a CMA-based method for reducing mutual coupling of Vivaldi antennas in a wide band is proposed. The MMA of Vivaldi antennas is analyzed. The modes which has large modal mutual admittance at several frequency points are observed. By comparing the eigencurrents which contribute to mutual coupling much, the critical places of those modes are found. Inductive loads are used to suppress such eigencurrents so that the mutual coupling can be reduced.


(a)

(b)

Fig. 8. Photograph of: (a) original antennas, and (b) optimized antennas with slot and inductive loads.



(a)

(b)

(c)

Fig. 9. The result of (a) Simulated and measured S-parameter of original antennas (b) Simulated and measured S-parameter of optimized antennas, and (c) compared for measured S21 between original antennas and optimized antennas.

Numerical and experimental results are shown to verify this method. The mutual coupling of Vivaldi antennas is reduced effectively in the frequency range of 1 to 3 GHz. In addition, radiation pattern performs better after optimization. The results show that CMA is effective to reduce mutual coupling of broadband antennas.

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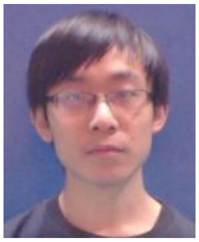

Zhenpeng Ma received the B.S. degree from Beihang University (BUAA), Beijing, China in 2017. He is currently pursuing master's degree in Beihang University. His current research interests include characteristic mode analysis and antenna mutual coupling. He was a volunteer in ACES China, 2018.

Qi Wu received the B.S. degree from East China Normal University, and Ph.D. degree from Shanghai Jiao Tong University in 2004 and 2009, respectively. He joined the faculty of Beihang University, in 2009, now he is an Associate Professor. During 2014 and 2016, he was an Alexander von Humboldt Fellow at Technical University of Hamburg, Germany.

Wu has authored over 40 journal papers, one book in Chinese and holds 10 Chinese patents. His research interests include broadband antennas, computational electromagnetics, and related EMC topics.

Wu received several awards including the Young Scientist Award from the International Union of Radio Science (URSI) in 2011, the Nominee Award for Excellent Doctoral Dissertation from the National Minister of Education in 2012. Wu was the TPC Co-chair of ACES China 2018.