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RECONFIGURABLE YAGI-UDA SUBSTRATE FOR RADAR CROSS SECTION REDUCTION OF PATCH ANTENNA

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Abstract—In this paper, a new Yagi-Uda substrate is proposed to obtain radar cross section (RCS) reduction. The Yagi-Uda substrate on which three kinds of metal microstrip lines are etched is put directly on the top of a patch antenna and can reduce RCS sharply by steering the direction of reflecting wave at resonant frequencies. Using a reconfiguration technique, the antenna can radiate without the substrate's effects. When the antenna does not need to work, the Yagi-Uda substrate works to reduce the RCS of the antenna. Besides, the resonant frequencies can be shifted by reconfiguring the Yagi-Uda substrate, so the RCS can be reduced in a broad frequency band.

1. INTRODUCTION

Microstrip patch antennas have many advantages such as: lightweight, low-profile, conformal and easy manufacturing, and do not disturb the aerodynamic properties of platforms. These advantages make them very popular in aerospace applications. Modern aircrafts do not hope to be found by enemy's radars, and radar cross section (RCS) is an important parameter to describe the stealth ability. The surface of an aircraft can have low RCS by using some radar-absorbing materials or shaping methods. However, these methods do not fit for antennas because of the destroying of the radiation performance. Therefore, a low RCS antenna is an important researching part of the overall RCS reduction project of a stealth object.

A variety of RCS reduction techniques have been applied to patch antennas. Generally, these techniques are sorted by two classes: full-time and part-time. The former can reduce RCS all the time, no matter whether an antenna works or not. Examples of these techniques are lumped loading technique [1, 2], covering lossy substrates technique [3] and adding slot and shorting post technique [4, 5]. This kind of techniques affects the antennas' structure or radiation more or less. The latter is a method that can reduce RCS when an antenna does not work. This kind of techniques does not affect antenna's radiation while the antenna works. As a cost, the RCS is not reduced while the antenna radiates. To realize this function, a thought of reconfiguration is mostly considered. In [6–9], a ferrite cover layer or ferrite substrate is used to reduce RCS. In [10], the authors used metallic electromagnetic band-gap materials to construct two states named transmission and stealth states. Transmission state maintains antenna radiation while stealth state reduces RCS. Additionally, a phase-switched screen is mentioned in [11–16]. Pin diodes are incorporated in a FSS structure to change the layer impedance to get different states.

In this paper, a new Yagi-Uda substrate is put directly on the top of ground as well as a patch antenna. Using a reconfiguration technique, the antenna can radiate without the substrate's affects. When the antenna does not need to work, the Yagi-Uda substrate works to reduce the RCS of the antenna.

2. YAGI-UDA SUBSTRATE

2.1. Structure and Performance

A Yagi-Uda antenna has a feeder, several directors and reflectors. The antenna can steer the beam peak to the director direction because of the mutual coupling affection, which can also be used in the RCS reduction by leading the beam peak of the reflect wave to the safe direction. For monostatic RCS, the safe direction means the direction away from the arrival radar direction. We use this thought to build a Yagi-Uda substrate to reduce RCS.

There is a Yagi-Uda substrate, shown in Fig. 1, on the top of a metal ground directly. The Yagi-Uda substrate is composed of three different parts. The three components are named as feeder, reflector and director according to the lengths of the original Yagi-Uda antenna, although the feeder has no feed, the reflector directs beam and the director reflects beam at some frequencies. The distances between two adjacent components which are metal microstrip lines etched on the substrate are the same. That is different from the traditional Yagi-Uda structures. The reason will be explained later in Section 3.

The main difference from Yagi-Uda antenna is that the Yagi-Uda substrate is passive, and has no real feed in the structure. The structure works depending on the incident waves. When radar wave arrives, currents will be stimulated on the surface of the microstrip lines. The

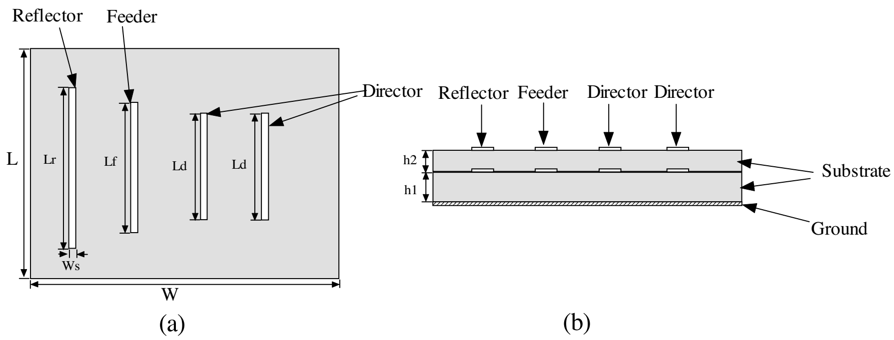

Figure 1. Metal ground with a Yagi-Uda substrate cover, (a) top view, (b) side view.

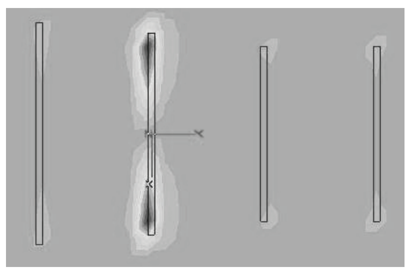

Figure 2. Current density of the strips.

current density of the strips is shown in Fig. 2. Because of the mutual coupling and the different lengths of the three components, the peak beam of the reflection is tilted to the horizontal direction at certain frequencies. Polarization is also important for this structure. When the linear polarization direction of radar wave is along the metal strips' direction, the structure can have the maximum effect. In this paper, the RCS means monostatic RCS at an incident angle of $\theta = 0°$ and $\varphi = 0°$. And all the radar waves are linear polarization along the strips' direction.

Three cases are simulated by using HFSS to verify the above concept. In case 1, there is only a metal ground. And in case 2, there is a same size metal ground covering a tow-layer Yagi-Uda substrate shown as in Fig. 1. The length L and width W of the Yagi-Uda substrate are 31.2 mm and 46 mm respectively. The thicknesses of each substrate are $h_1 = 0.9$ mm and $h_2 = 1.5$ mm. The width Ws of each strip is 0.4 mm. The reflector length $L_r = 13.2$ mm. The feeder length $L_f = 12$ mm. The director length $L_d = 10.4$ mm. In

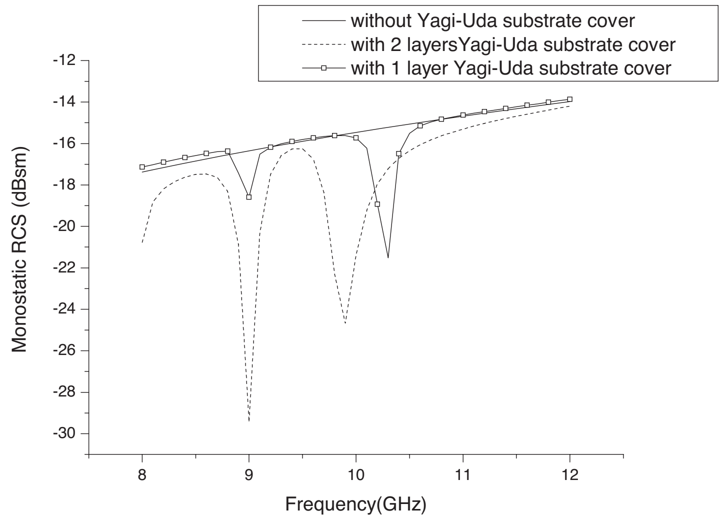

Figure 3. Monostatic RCSs of a metal ground with and without a Yagi-Uda substrate cover.

case 3, there is a same size metal ground covering a one-layer Yagi-Uda substrate. The thickness of the substrate is 0.9 mm, and the other parameters are the same with the two-layer case. The planar radar wave of 8–12 GHz comes from the perpendicular direction of the ground. Fig. 3 depicts the comparison of monostatic RCSs of the three cases. Apparently, the RCS reduction of 1 layer case is much weaker than that of 2 layers case. That is the reason why we use tow layers of the substrate: the mutual coupling effect is too weak to change the direction of reflecting wave if there is only one layer. In two-layer case, the monostatic RCSs are heavily reduced around 9 and 10 GHz. The maximum reduced value is about 12 dBsm around 9 GHz. And at 10 GHz the RCS reduction is about 10 dBsm. In the whole frequency range of 8–12 GHz, the RCSs are lower than the corresponding RCSs of a metal ground without a Yagi-Uda substrate cover. Fig. 4 shows the reason of this reduction. The Yagi-Uda substrate tilts the direction of reflecting wave at a resonant frequency of 9 GHz.

From Fig. 3, the RCS-reducing frequencies are around 9 and 10 GHz. The resonant frequencies can be chosen by selecting different lengths of Yagi-Uda components. In other words, the lengths of microstrip lines decide the resonant frequencies. In this paper, we fix the length scale between reflector and feeder being 1.1, and scale between director and feeder being 0.9. So, we only adjust the length of feeder to shift the RCS-reducing frequencies. Fig. 5(a) shows

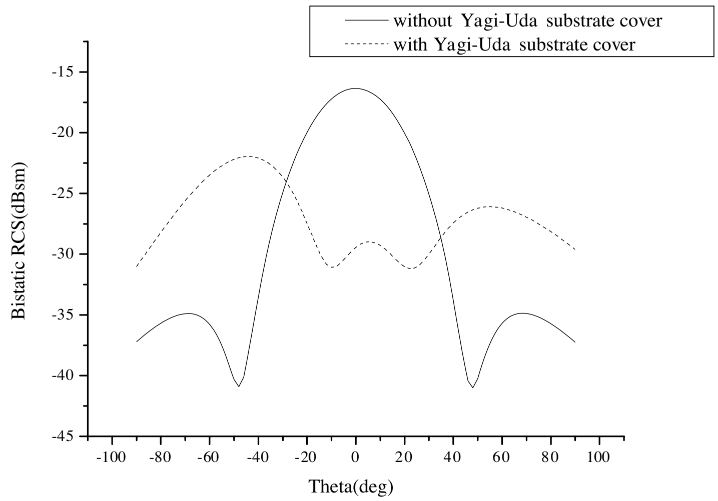

Figure 4. Bistatic RCS between of a metal ground with and without a Yagi-Uda substrate cover at 9 GHz.

monostatic RCS of 9 mm and 12 mm length feeder. The resonant frequencies of the 9 mm-feeder case are around 9.5 and 10.5 GHz. It is clearly that the lengths of lines can decide the RCS troughs.

CST is a simulation software based on time-domain method. It is different from HFSS which uses finite element method. Therefore, the results of CST have the value of comparison to verify our idea. We re-simulate the structure of Fig. 1 using CST. The result is shown in Fig. 5(b). The lower trough of the 12 mm-feeder case RCS is divided into two troughs. Except that, there is only a little frequency shift between the CST results and the HFSS results. That proves our concept is correct.

2.2. Reconfiguration

Since the RCS-reducing frequency can be changed only by selecting different strip lengths, we could use some reconfiguration techniques to expand the frequency range of RCS reduction.

MEMS switches are light and small, so they are very suitable for reconfiguration switches. Broadband RF MEMS switches have nearly ideal switching behavior while maintaining low power dissipation. The insertion loss of a MEMS switch is less than 0.2 dB from DC through 40 GHz when the switch is closed. When it is open, the switch isolation is > 50 dB at low frequencies and it gradually decreases to 27 dB at

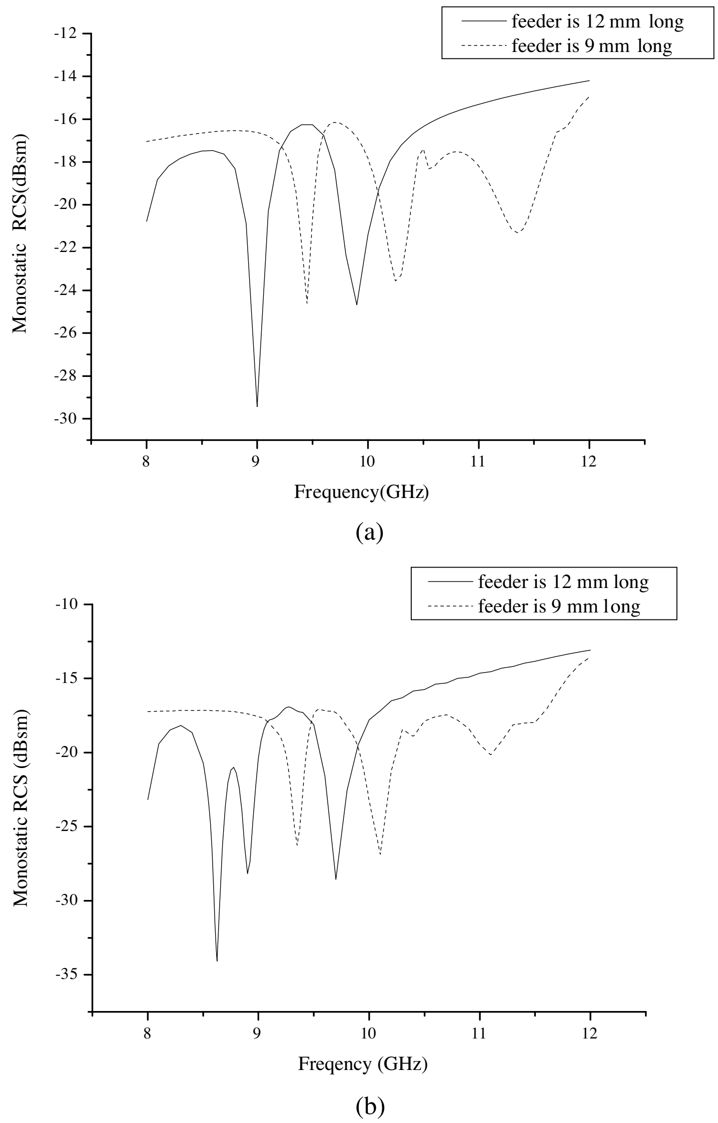

Figure 5. Monostatic RCS of a metal ground with a Yagi-Uda substrate cover having different feeder lengths, (a) HFSS results, (b) CST results.

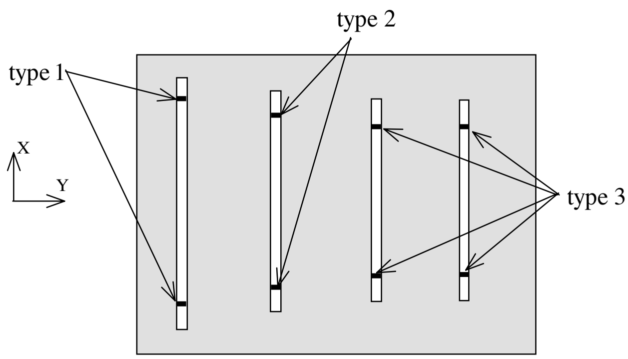

Figure 6. Structure of reconfigurable Yagi-Uda substrate.

40 GHz [17]. In simulation, when the switch is open, it can be replaced by a PEC patch. When the switch is closed, it can be substituted by a slot. The size of switch is 0.4 mm × 0.2 mm. Experiments in [18] showed that the results of the ideal switch model in HFSS are consistent with the results of real MEMS switch.

Using MEMS switch to design reconfigurable Yagi-Uda substrate is shown in Fig. 6. MEMS switches are added at three kinds of positions. According to the positions, we sort the switches into three types: type 1, type 2 and type 3. Two switches which are inserted into the reflector are classified as type 1. Type 2 also has two switches inserted into the feeder. And type 3 has four switches inserted into the directors. Each type of switches is symmetrical about y-axis. All the switches are open or closed at the same time. When open, Yagi-Uda substrate acts as a 9 mm-feeder case. When closed, Yagi-Uda substrate acts as a 12 mm-feeder case. Fig. 7 shows the monostatic RCS of the structure when the switches are open or closed from 8 GHz to 12 GHz. Compared with Fig. 5, switch-closed condition is actually the same as the 12 mm-feeder case. When switches are open, the only difference is that the lowest point of RCS has a negligible frequency shift.

We can change the length of strips by changing the conditions of switches. And the resonant frequency can be selected by the length of microstrip lines. So we can choose different states to reduce RCS according to the radar wave frequencies. This expands the frequency range of RCS reduction.

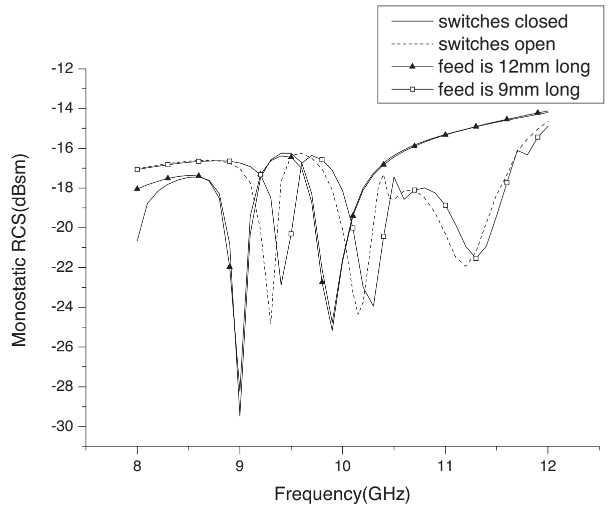

Figure 7. Monostatic RCS of the Yagi-Uda structure when switches are open or closed.

3. ANTENNA RCS REDUCTION

3.1. Yagi-Uda Substrate for Patch Antenna

When a patch antenna is covered with a Yagi-Uda substrate, the steering effect will influence antenna radiation. To keep the antenna's radiation property, we need two approaches to eliminate the deflection. The first one is to let the distances between feeder and reflector, feeder and director, and two directors the same, because the asymmetry may disturb the radiation pattern. The second one is to add more reconfiguration switches to adjust the pattern. There are six types of switches. Each type of switches is symmetrical about y-axis and has different functions. Types 1, 2 and 3 can select the lengths of strips as section 2.2 presented. Types 4, 5 and 6 are the newly added ones. Type 4 has two switches. They are inserted into reflector. Four switches which are inserted into the directors are classified as type 5. Types 4 and 5 make feeder, reflector and director to be the same length. Type 6 has eight switches which are inserted into the middle part of the reflector, feeder and directors. When they are open, the effects of the Yagi-Uda substrate are lessened. Because the resonant frequency is decided by the lengths of strips, the short strips' resonant frequency is away from the antenna's radiation frequency and the strips do not disturb the radiation pattern of the antenna. The final structure of

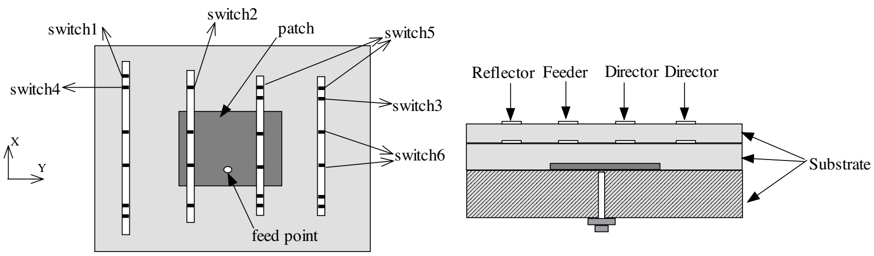

Figure 8. Rectangular patch antenna with a Yagi-Uda substrate cover.

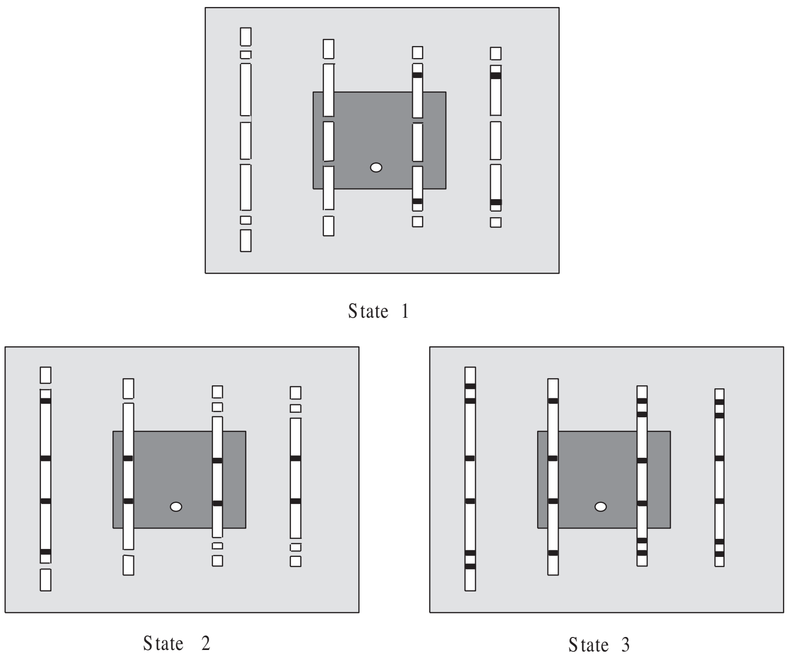

Figure 9. Three states of antenna with a Yagi-Uda substrate cover.

rectangular patch antenna with a Yagi-Uda substrate cover is shown in Fig. 8.

The antenna has three states shown as in Fig. 9. State 1 is the radiation state, and antenna acts like normal patch antenna. State 2 is the low-RCS state. State 3 is another low-RCS state. The difference between states 2 and 3 is that they have different frequencies of lowest monostatic RCS.

In state 1, switch types 1, 2, 4, 5 and 6 are open and only switches

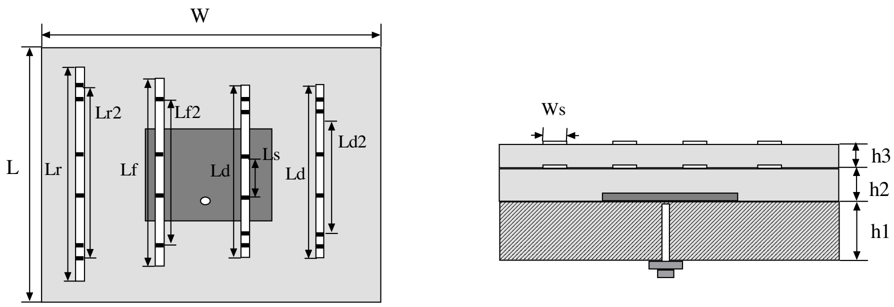

Figure 10. Parameters of antenna with a Yagi-Uda substrate cover.

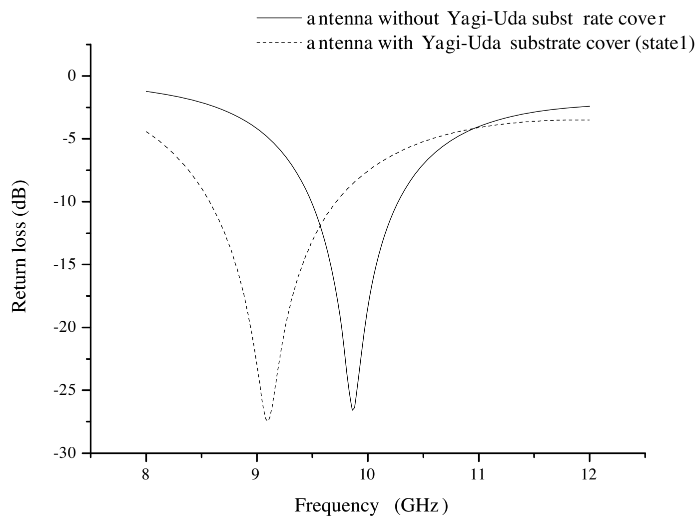

Figure 11. Return loss of antenna with and without a Yagi-Uda substrate cover in state 1.

of type 3 are closed. From Fig. 9, we can see that the feeder, reflector and director are truncated by the open switches. The short sections do not affect the radiation at operation frequency. We close switches of type 3 to retain the symmetry of the directors about y-axis. In state 2, switches of types 4 and 6 are closed, while others are open. It is like the 9 mm-feeder case in section 2.1. In state 3, all the switches are closed. It acts as the 12 mm-feeder case in section 2.1.

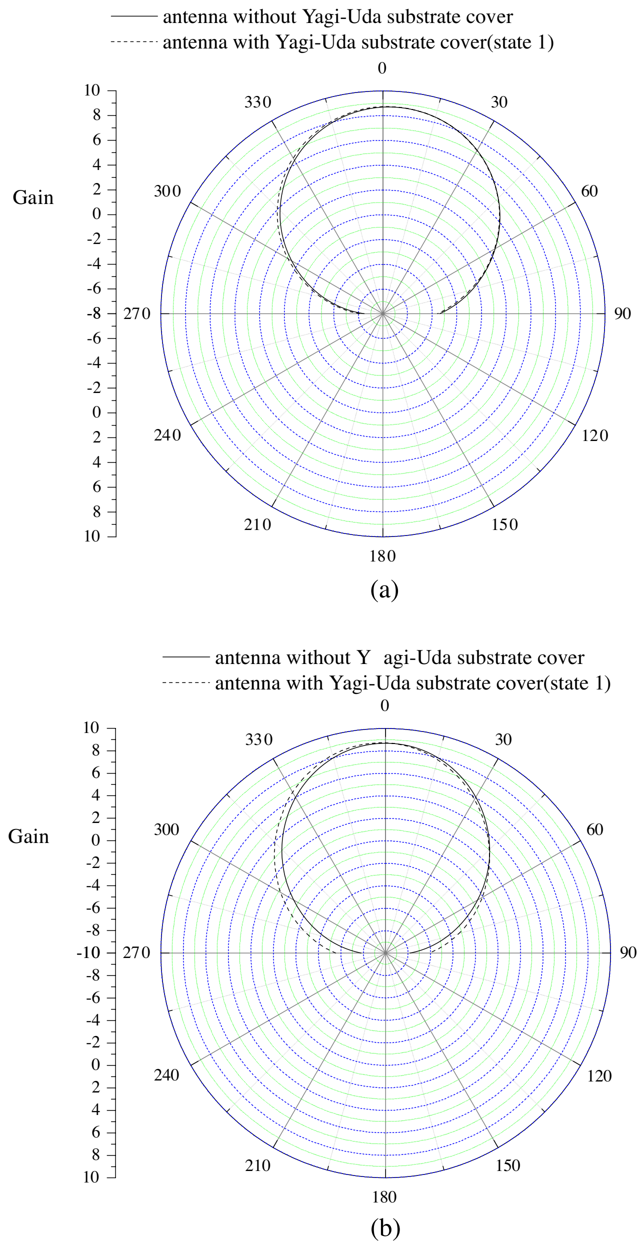

Figure 12. Gain pattern of antenna with and without a Yagi-Uda substrate cover in state 1, (a) E plane, (b) H plane.

3.2. Antenna Structure and Performance

The key parameters of Yagi-Uda substrate are displayed in Fig. 10. The length L and width W of the substrates are 31.2 mm and 46 mm respectively. The thicknesses of each substrate are $h_1 = 1.6$ mm, $h_2 = 0.9$ mm and $h_3 = 1.5$ mm, respectively. All of the substrates are Rogers duroid 5880 whose relative permittivity is 2.2. The switches dimensions are $0.2\,\text{mm} \times 0.4\,\text{mm}$. The width of each strip is 0.4 mm. The reflector lengths: $L_r = 13.2$ mm and $L_{r2} = 9.9$ mm. The feeder lengths: $L_f = 12$ mm and $L_{f2} = 9$ mm. The director lengths: $L_d = 10.4$ mm and $L_{d2} = 8.1$ mm. The distance of L_s is not important and in our model $L_s = 4.1$ mm.

Figure 11 and Fig. 12 depict the return loss and the Gain of a patch antenna with and without a Yagi-Uda substrate cover. The Yagi-Uda substrate is in state 1. The Yagi-Uda substrate only changes the operation frequency of the patch antenna. And the gain patterns keep almost the same in E plane and H plane.

The RCSs of antenna with and without a Yagi-Uda substrate cover in state 1 is shown in Fig. 13. There is only one RCS trough in the figure. And the lowest point of RCS is near the operation frequency. The reason is that the antenna as a receiving one absorbs the radar power in its operation frequency. And in our model, the load

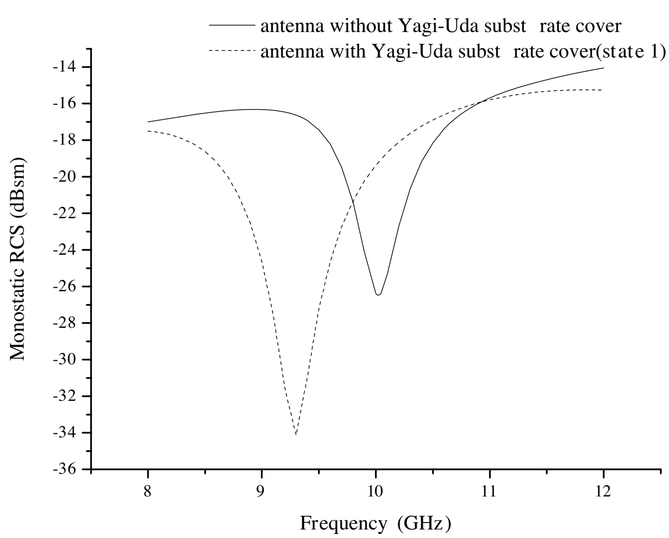

Figure 13. Monostatic RCS of antenna with and without a Yagi-Uda substrate cover in state 1.

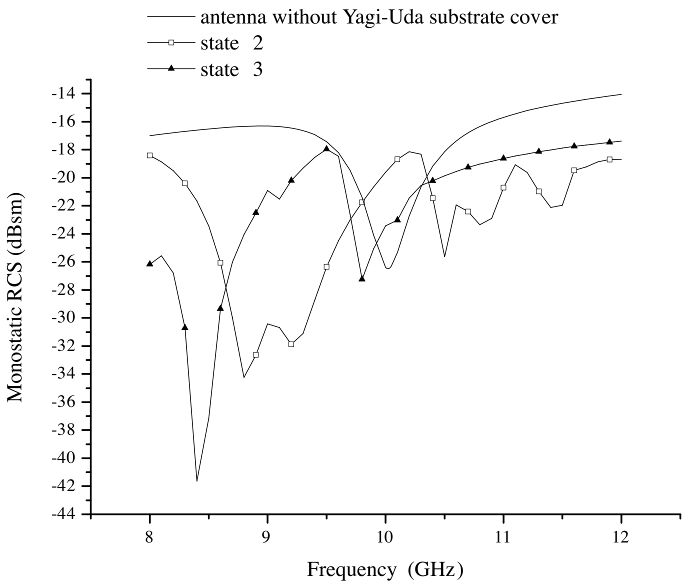

Figure 14. Monostatic RCS of state 2 and state 3 and antenna without a Yagi-Uda substrate cover.

is perfectly matched, so there is no re-radiation scattering, which is called mode scattering, of the antenna. It is shown that state 1 has no effect of RCS reduction. It only shifts the RCS trough.

Figure 14 shows that when Yagi-Uda substrate is in state 2 or state 3, the RCSs are reduced heavily at different resonant frequencies. The maximum reduction is about 26 dBsm in state 2, and in the state 3 the reduction of RCS is up to 20 dBsm. We can use different states to realize low monostatic RCS according to the incoming radar wave's frequency. From the whole frequency range of 8–12 GHz, the RCS is lower than the antenna without a Yagi-Uda substrate, except a narrow frequency band between 10 and 10.5 GHz in which the RCSs are low originally. Thus, combining these tow states, the RCS can be reduced in a large frequency range.

4. CONCLUSION

In this paper a Yagi-Uda substrate is proposed to reduce RCS sharply by steering the direction of reflecting wave at resonant frequencies. It is composed of two layers' feeder, reflector and director. Using reconfiguration technique, the antenna radiation can be remained and its RCS can be reduced in a large frequency range. If adding more switches, the state number of the Yagi-Uda substrate would increase, and a wider low-RCS frequency band could be reached. Two commercial simulation softwares are used to verify the idea. Furthermore, this structure is sensitive to the polarization and the incoming direction of radar wave, so further improvement needs to be done in the future.

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