Progress In Electromagnetics Research, Vol. 130, 153–168, 2012

SUBSTRATE INTEGRATED WAVEGUIDE FREQUENCY-AGILE SLOT ANTENNA AND ITS MULTIBEAM APPLICATION

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Abstract—A new technique for designing the substrate integrated waveguide (SIW) frequency-agile slot antenna is presented in this paper. Similar to the metallic waveguide counterpart, the SIW is a uniconductor guided-wave structure and inherently difficult in the electronically tunable applications. To solve this problem, a single slot etched on the top conductor layer of a conventional antenna is instead of two slots to construct an isolated area, which is convenient for the DC bias. The electric length of slots can then be adjusted through two shunt varactors welded near the center of slot. As such, a SIW frequency-agile slot antenna is realized and fabricated to cover the frequency of $2.30 \sim 2.74$ GHz with different bias voltages. Experiments verify our theory analysis and design process. Then, a frequency-agile multibeam antenna is developed to cover several frequency bands while switching between four different radiation patterns pointing at different spatial locations for each frequency. It presents an excellent candidate for software and cognitive radio system applications.

1. INTRODUCTION

Reconfigurable antennas have received significant attention for their applications in communications because of their selectable fundamental characteristics [1–7]. As an important kind of antennas, the slot antenna is a good solution for frequency-agile applications [8–10]. The slot can be fed by a microstrip line or a CPW, but there exist some problems. The size of the ground plane affects the electrical and

Received 16 June 2012, Accepted 8 August 2012, Scheduled 9 August 2012
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radiation parameters of a slot antenna, such as the radiation pattern, resonant frequency, and gain. Besides, the feed line and the radiator are placed at different sides of the substrate, which leads to difficulty in separating circuits from environment and improving mechanical strength. As such, the waveguide-fed slot antenna is a better choice compared with the microstrip version, especially in the high frequency application. However, only a little research [11] about this topic is published since it is difficult to implement electrically tuning for a waveguide component.

Substrate integrated waveguide (SIW) can be regarded as a dielectric-filled rectangular waveguide. This planar scheme combines the excellent features of both planar transmission lines and non-planar waveguide [12–22]. A SIW slot antenna is developed as described in [23] and has been applied in many designs. Very recent years, researchers try to realize some SIW frequency-agile components, including filter [24], VCO [25], phase shifter [26], and antenna [27, 28]. Unlike those conventional planar transmission lines, such as the microstrip line, the SIW is a uniconductor guided-wave structure and has the same electric potential for each metallic surface. If only one slot is employed in the design of a frequency-agile slot antenna, the DC bias for varactors is difficult to supply. One possible way is to feed a varactor through a bonding line [25]. It is not a good choice because the bonding line would deteriorate the radiation pattern. A two-layer structure including a special feed layer can be employed to offer the DC bias in the filter design [24]. But the radiator slot would be covered by the feed layer, which is fundamental unfeasible for antenna applications. A microstrip-fed frequency tunable slot antenna usually prints a bias line on the same side of it signal feed line. This method may not be practicable in the SIW design. If several additional slots are etched on the conductor layer of a SIW to realize a DC bias circuit, the SIW's electric property will be influenced much more and a unwanted parasitic resonate phenomenon caused by those slots will be observed.

In this paper, we try to realize a SIW slot antenna with frequency continuously tunability. The proposed antenna utilizes two shunt varactors that effectively change the slot's electrical length. A simple way is employed to deliver DC bias for the varactors. Such an antenna can cover the frequency range from 2.30 GHz to 2.74 GHz controlled by the reverse voltage of $2 \sim 15$ V. Good performance is shown through experiment. After that, a frequency-agile multibeam antenna is developed by such four proposed slot antennas. It has the ability of frequency-agile and beam-switched at the same time. Compared with the broadband and multiband multibeam antenna, our structure may be the best choice considering its inherent out-of-band noise rejection.

2. SIW FREQUENCY-AGILE SLOT ANTENNA

2.1. Configuration

Figure 1 illustrates the physical configuration of the proposed SIW frequency-agile slot antenna. The white and gray areas stand for the substrate and conductor, respectively. Such an antenna has two slots with different offset values. Therefore, the center conductor cover is separated and connected to the DC contact pad through two open stubs and a high-impedance microstrip line in order to provide DC bias for varactors. Two same varactors are mounted across the slot near its center.

As is well known, a shunt slot on the broadside of waveguide interrupts the transverse current and can be represented by two-terminal shunt admittance [23]. In our design, two slots are instead of the single one. This structure can also be represented by two-terminal shunt admittance as shown in Fig. 2, because its impedance is a maximum at the resonant frequency in simulation. Here, the imaginary part of the input admittance Y_{in} must be zero when the slot resonates.

Two same varactors are connected in parallel. They are able to provide additional capacitive reactance for the loop and then change the resonant frequency for satisfying the condition of parallel resonance. Certainly, a larger capacitance leads to a lower operation frequency. If the two slots are arranged at the center of the waveguide, the energy cannot be radiated out, which is similar to the conventional waveguide single slot antenna.

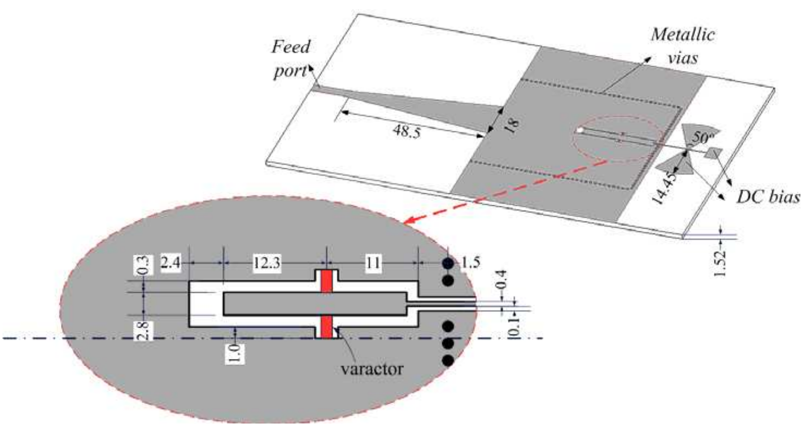

Figure 1. Configuration of the proposed SIW frequency-agile slot antenna. (Unit: mm).

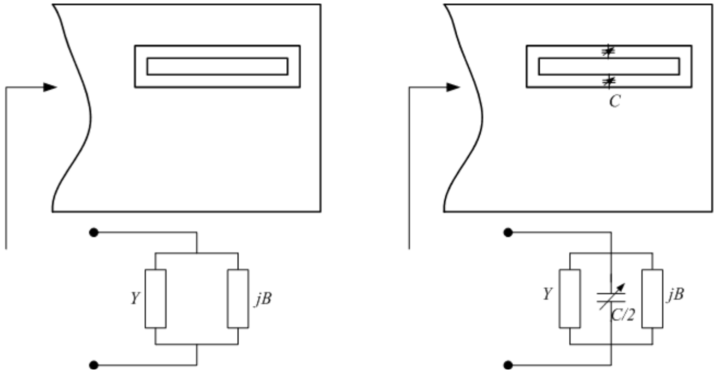

Figure 2. Equivalent circuit of the proposed dual-slot SIW antenna.

2.2. Design Process

A six-stage design process for the proposed SIW frequency-agile slot antenna is listed as follows:

1) According to the desired tunable range of frequency, $f_{\min} \sim f_{\max}$ (GHz), the SIW's dimension, including the actual width of input SIW, a (mm), the diameter of metallic via, d (mm), and the space between adjacent vias, s (mm), is determined to meet the waveguide's single-mode condition. Thus:

$$f_{\min} > \frac{300}{2w\sqrt{\varepsilon_r}}, \quad f_{\max} < \frac{300}{w\sqrt{\varepsilon_r}} \tag{1}$$

where

$$w = a - \frac{d^2}{0.95 \times s} \tag{2}$$

2) The initial length of each slot, l (mm), can be calculated by

$$l = \frac{150}{f_{\max}\sqrt{\varepsilon_r}}, \tag{3}$$

which is a half of operation wavelength at the highest frequency. Loading the SIW slot antenna with capacitors shifts the resonant frequency down. Thus a reasonable l should be chosen less than the value calculated by (3) considering the non-zero minimal capacitance of a commercial varactor. The initial spacing between slot and short-end wall, e (mm), can be calculated by

$$e = \frac{75/f_{\max}\sqrt{\varepsilon_r}}{\sqrt{1 - (150/wf_{\max}\sqrt{\varepsilon_r})^2}}, \tag{4}$$

which is a quarter of the guide wavelength at the highest frequency. With the same consideration, e can be chosen less than the value calculated by (4).

3) A varactor with proper tunable range of capacitance is selected to cover the desired frequency range.
4) The offsets of slots and the position of varactors are optimized to achieve a better matching and radiation performance over the whole frequency band.
5) The DC bias line is designed. The window in the short-end wall should be as narrow as possible to avoid the parasitic operation mode.
6) At last, the SIW TE_{10} mode should be transferred to the microstrip quasi-TEM mode with good matching over the frequency tunable range.

2.3. Experiment

In this work, the frequency variable range is set within S-band to validate our idea. The used varactor diode is Skyworks SMV1405, which offers a tunable range of capacitance from 0.63 pF to 2.67 pF with the different reverse voltages. As shown in Fig. 3, a SIW frequency-agile slot antenna was fabricated based on the Taconic RF35 substrate with the permittivity of 3.5 and height of 1.52 mm. The actual width of input SIW is 50 mm, the diameter of metallic via is 0.4 mm, and the space between adjacent vias is 0.8 mm. Other dimensions have been depicted in Fig. 1. The calculated l and e by (3) $\sim$ (4) are 29.20 mm and 18.04 mm, while the final optimized ones are 25.70 mm and 14.35 mm, respectively, which is agree with our expectation. The simulated E-fields of the proposed antenna at different frequencies are shown in Fig. 4.

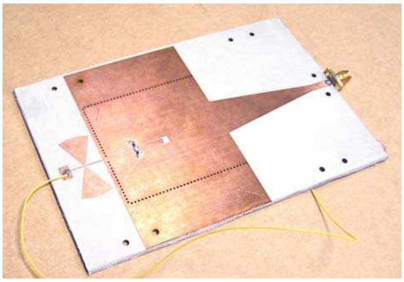

Figure 3. Configuration of the fabricated SIW frequency-agile slot antenna.

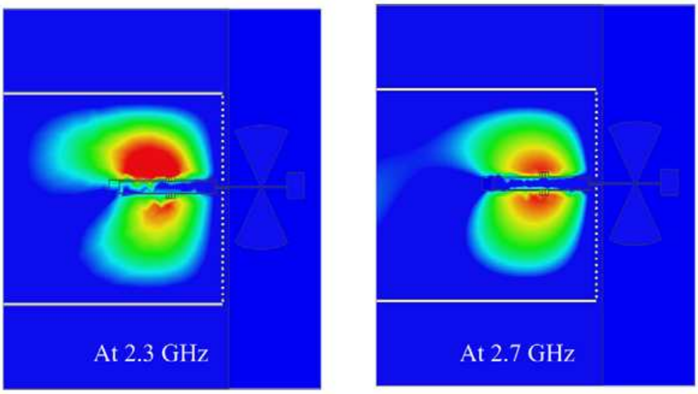

Figure 4. E-fields of the proposed SIW frequency-agile slot antenna.

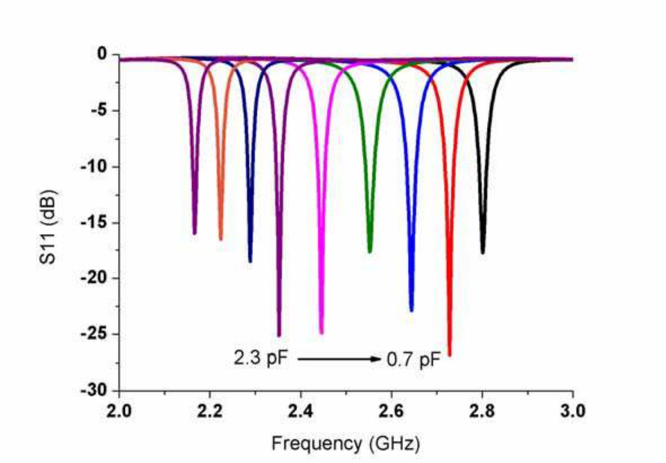

Figure 5. Simulated S_{11} of the proposed frequency-agile antenna versus capacitances.

Figure 5 shows the simulated reflection coefficients with different capacitances. Serving as counterparts, the measured S_{11} results with different bias voltages is shown in Fig. 6. When the applied reverse voltage changes from 2 V to 15 V, the resonant frequency is tuned from 2.30 GHz to 2.74 GHz with better than -7 dB reflection coefficients. A summary of measured results including operation frequency and reflection for each DC bias is presented in Table 1. The antenna's performance is deteriorated as the capacitance increases.

Normalized simulated and measured radiation patterns are shown in Figs. 7 ∼ 9. In this experiment, different capacitors are employed instead of varactors due to the difficulty of DC bias supply in our anechoic chamber. It is noted that the typical radiation patterns for a conventional SIW slot antenna are maintained. The gain and efficiency versus frequency is shown in Fig. 10. As observed, the radiation gain is lowered with the decreased bias voltage when the varactor capacitance is increased. This is because the electrically smaller size at lower

Table 1. Measured results of the proposed SIW frequency-agile slot antenna.

Reverse Voltage	Frequency	S_{11}
2 V	2.30 GHz	−7.01 dB
2.6 V	2.37 GHz	−8.88 dB
3 V	2.41 GHz	−10.47 dB
4 V	2.48 GHz	−12.56 dB
5 V	2.53 GHz	−13.26 dB
7 V	2.61 GHz	−13.43 dB
10 V	2.68 GHz	−13.52 dB
15 V	2.74 GHz	−14.62 dB

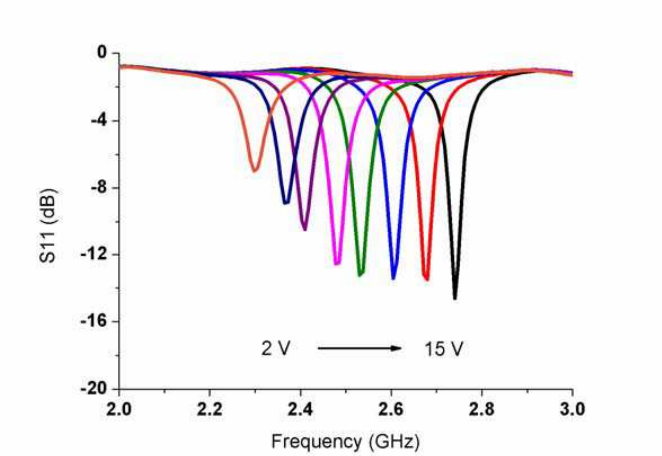

Figure 6. Measured S_{11} of the proposed frequency-agile antenna versus bias voltages.

frequency deteriorates the antenna radiation capability. Furthermore, the capacitor loss and fabrication tolerance lead to lower measured gains compared with the expected ones.

Table 2 lists the comparison of the proposed SIW frequency-agile slot antenna and other tunable antennas, including the number of used varactor, tunable frequency ratio $f_{\max}/f_{\min}$, and the antenna

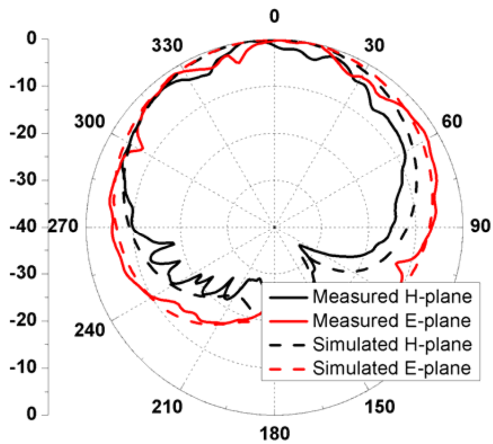

Figure 7. Patterns of the proposed frequency-agile slot antenna at 2.46 GHz.

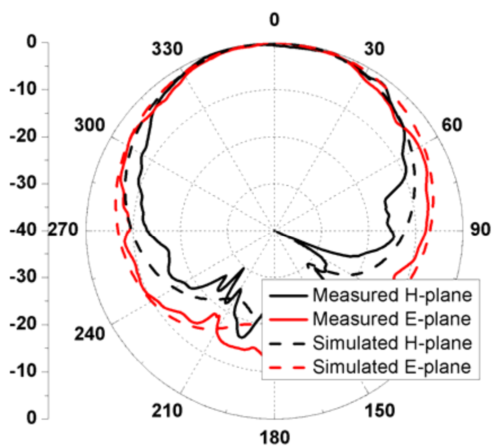

Figure 8. Patterns of the proposed frequency-agile slot antenna at 2.61 GHz.

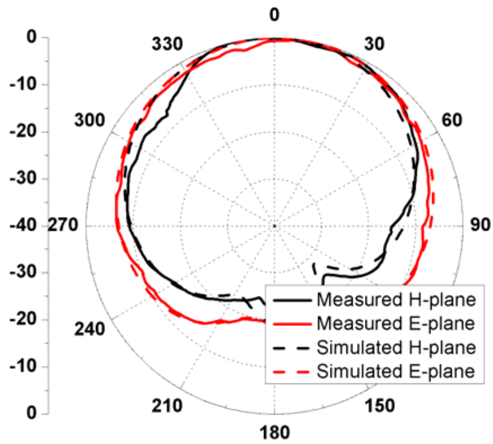

Figure 9. Patterns of the proposed frequency-agile slot antenna at 2.7 GHz.

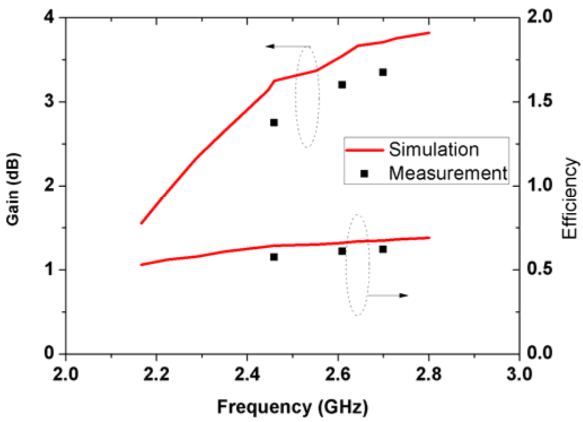

Figure 10. Gain and efficiency of the proposed antenna versus frequency.

performance. The results of the lower resonant frequencies for a dual-band antenna are selected to achieve a justified comparison. That is because other single-band tunable antennas usually operate at their first resonant frequencies. This comparison demonstrates that our structure has better performance in the gain and efficiency over the whole tunable range.

Table 2. Comparison of the proposed SIW frequency-agile slot antenna and other tunable antennas.

	in [2]	in [3]	in [6]	in [7]	in [8]	in [9]	in [10]	Our work
No. of Varactor	4	1	1	3	1	1	8	2
$f_{\max}/f_{\min}$	1.34	1.24	1.13	1.96	1.08	1.8	2.2	1.2
$S_{11_{\max}}$ (dB)	–	−14	−6	−11	−20	−18	−7.5	−7
$\text{Gain}_{\max}$ (dBi)	–	1.3	−2.95	5.04	0.6	5	1.71	3.45
$\text{Gain}_{\min}$ (dBi)	–	–	–	−0.13	0.4	−2	−8.25	1.2
$\text{Efficiency}_{\max}$	–	39%	–	–	–	76%	73%	64%
$\text{Efficiency}_{\min}$	–	–	–	–	70%	18%	8.6%	45%

3. FREQUENCY-AGILE MULTIBEAM ANTENNA

Here, a frequency-agile multibeam antenna is developed to cover several frequency bands while switching between four different radiation patterns pointing at different spatial locations for each frequency. It consists of a Butler matrix and a frequency-agile antenna array.

As is well known, the Butler matrix is one of the most famous techniques in the design of switched-beam antenna. As shown in Fig. 11, it is based on the use of four 90° 3 dB frequency-agile directional couplers connected together with two fixed phase shifters (45°) at corners. The measured S-parameters and phase characteristics of the fabricated Butler matrix are shown in Figs. 12 $\sim$ 13.

Then, this Butler matrix is cascaded with a 4-element SIW frequency-agile slot antenna array to construct a frequency-agile multibeam antenna as shown in Fig. 14. The distance between adjacent elements is 50 mm. The radiation patterns of the fabricated multibeam antenna excited at ports 1 and 2 at 2.61 GHz is shown in Fig. 15.

Now, the interference suppression of this frequency-agile multibeam antenna is investigated. With C of 1.2 pF, the proposed structure is operated at the center frequency of 2.61 GHz. As shown in Fig. 16, if there are some interference signals from other radio service at different operation frequency entering into the receiver, the performance of system may be highly susceptible to mutual interference and pronounced degradation. As such, high performance filters must be employed in order to attain better noise rejection. But for our structure, excited at port 2, the received power level at 345° are only 29%, 61%, and 69% for 2.4 GHz, 2.5 GHz, and 2.7 GHz, compared with the result of 2.61 GHz. It is demonstrated that the ability to eliminate mutual interfere is good for our proposed structure compared with the wideband or multi-band multibeam antenna. The filter requirements of front-end circuitry can be reduced due to its superior out-of-band rejection.

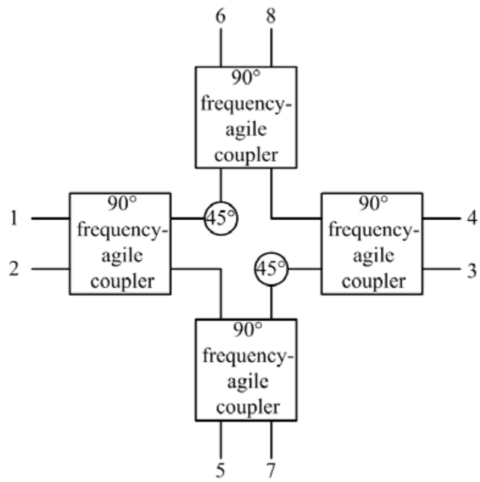

Figure 11. Configuration of the employed Butler matrix.

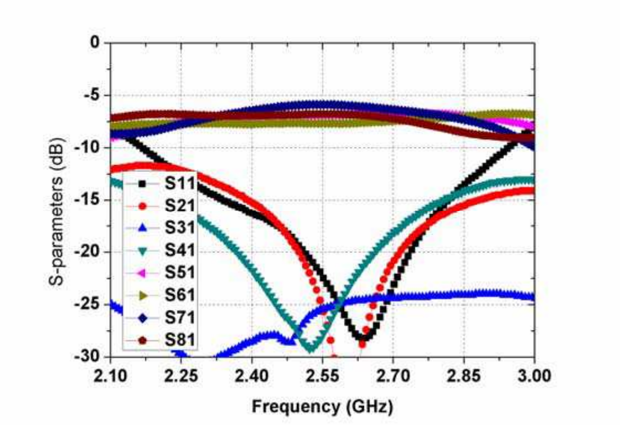

Figure 12. Measured S-parameters excited at port 1 of the fabricated Butler matrix.

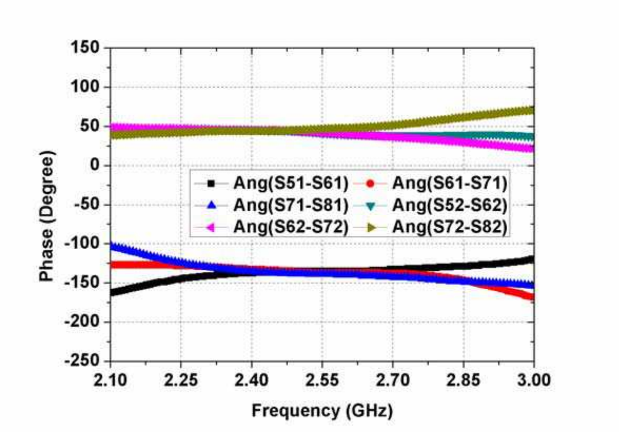

Figure 13. Measured phase excited at ports 1 and 2 of the fabricated Butler matrix.

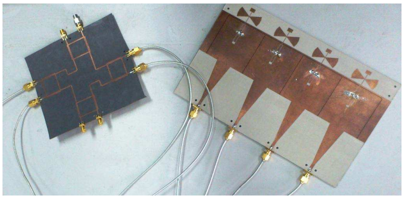

Figure 14. Fabricated frequency-agile multibeam antenna.

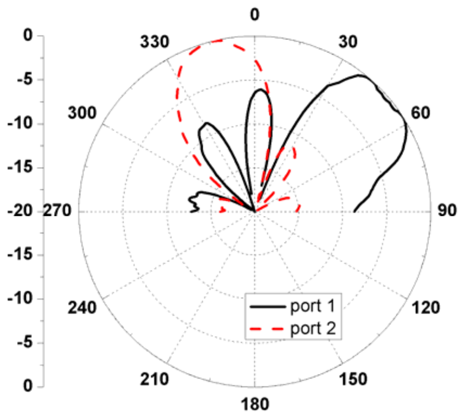

Figure 15. Radiation patterns of the fabricated frequency-agile multibeam antenna excited at different ports.

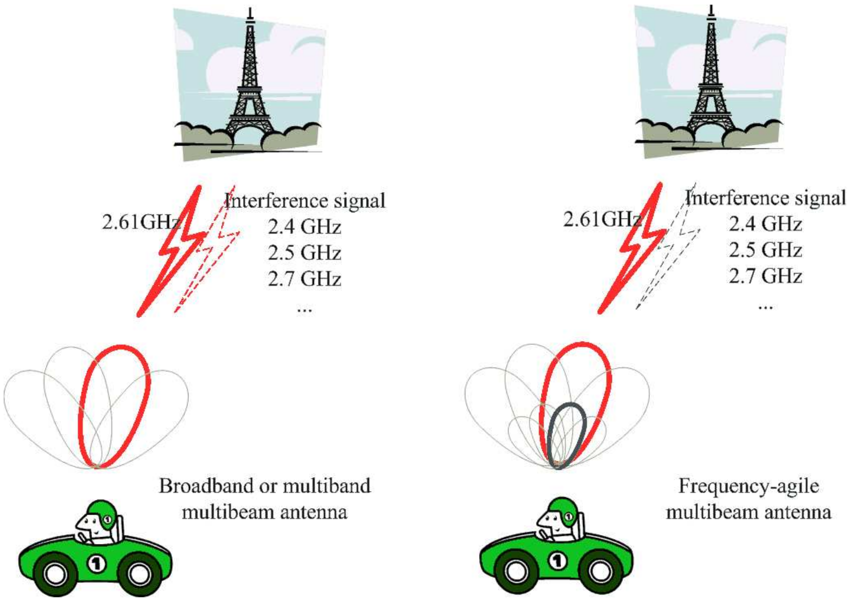

Figure 16. Frequency-agile multibeam antenna to suppress the interference signal.

4. CONCLUSION

A frequency-agile SIW antenna and a corresponding multibeam antenna are proposed and investigated, as well as experimented. Good performances are shown at different frequency, which prove that the proposed reconfigurable structure presents a great potential for wireless communication systems with cognitive capability. Considering SIW's good performance applied in high frequency band, this new concept can be employed in the design of high-frequency reconfigurable antenna by use of proper varactors, such as the ferroelectric capacitor.

ACKNOWLEDGMENT

This work is supported in part by the National Natural Science Foundation of China (NSFC) under grant 61001028, in part by China Postdoctoral Science Foundation under grant 2012M511918, in part by the Research Fund for the Doctoral Program of Higher Education of China (RFDP) under grant 20100185110014, and in part by the Fundamental Research Funds for the Central Universities under grant ZYGX2010J019.

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