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Switchless Reconfigurable Antenna with 360° Steering

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Abstract—A novel reconfigurable antenna capable of rotating a bi-directional pattern by 360° in azimuth is proposed. The antenna has two ports, no aperture switching components and offers a more compact solution than an array. It provides a reconfigurable pattern in the band 2.525 to 2.595 GHz and a fixed omnidirectional pattern from 2.235 to 2.725 GHz. The measured gains for four investigated configurations are between 2.1 dBi and 3.1 dBi with total efficiencies between 80% and 89%.

The antenna is intended to operate with software defined radio (digital beamforming or MIMO), where the potential of pattern generation using the dual-port antenna can be fully exploited. It offers multi-user pattern reconfiguration at low-cost within a limited volume.

Index Terms—Reconfigurable antenna, adaptive antenna, smart antenna, beamsteering, digital beamforming

I. INTRODUCTION

PATTERN RECONFIGURATION is a highly desired antenna property, enabling spatial multiplexing for modern communication systems. Many designs offer this capability, mainly employing *pin* diodes or MEMS switches, which route the surface current in the antenna aperture [1-7]. Although this approach offers pattern reconfiguration over a wide angular range, it suffers from many disadvantages. Most notably, the switches generate the same current distribution within the operating bandwidth, preventing the use of different radiation patterns for various channels. This practically excludes their use for point-to-multipoint communications systems (e.g. WLAN or LTE), where numerous terminal devices are at different locations and each channel requires independent patterns. This is not achievable with the antennas reported in [1-7].

Another difficulty stems from the way switches are

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controlled, i.e. the requirement for DC bias voltage. Its application necessitates extra circuitry, i.e. filters to separate DC and RF signals; a dedicated control unit to change the pattern; and copper tracks or cables to deliver the voltage to each switch. In addition, integration of multiple switches is challenging and introduces constraints into the design.

The proposed antenna offers a break-through in reconfigurable antenna technology, as it overcomes these limitations without the need for a spatially distributed antenna array. The antenna can reconfigure the pattern without the need for switches. It uses multiple ports integrated into a single device, with the steering realized by varying phase and amplitudes between the ports. A similar technique was previously used for null steering [8, 9]. The approach opens multiple novel applications, e.g. the pattern can be steered directly by a baseband transceiver, just by adjusting the I and Q components in the modulation plane [10]. Although conceptually similar to digital beamforming or “smart antennas”, the proposed antenna is a single device of size $\lambda/2$, with the possibility for further miniaturization. This allows substantial size reduction, or doubles the amount of antennas within the same volume. At the same time, most state-of-the-art digital beamforming or MIMO solutions are also compatible with the proposed device.

II. DESIGN

The key component to the antenna’s functionality is a circular patch (seen in Fig. 1) milled on Taconic™ RF-60 substrate ($\epsilon_r = 6$; $h_1 = 6$ mm), which operates at its second resonant mode. It is fed using two vias of radius R_v , which form 45° with respect to the disc center to excite two orthogonal modes (seen in Fig. 2). A hole of radius R_h (as seen in Fig. 1a) is milled around the vias to provide isolation from the lower conducting sheet. This sheet is a ground plane for both the patch and its feed circuitry located on the rear.

The bottom layer (green in Fig. 1) supports the patch feed network on the Taconic™ RF-35 octagonal PCB ($\epsilon_r = 3.5$; $h_2 = 1.5$ mm). This includes the 3 dB power divider and 90° phase shifter circuitry, both required for the desired electric field distribution. An SMA connector connects to the edge of the 50Ω line, forming port 2 of the antenna.

The top component is a copper monopole, located above the circular ground plane of radius R_l (i.e. metallization covering the top of RF-60 dielectric). It is fed by a 50Ω semi-rigid coaxial cable (port 1), through the center of the lower layers,

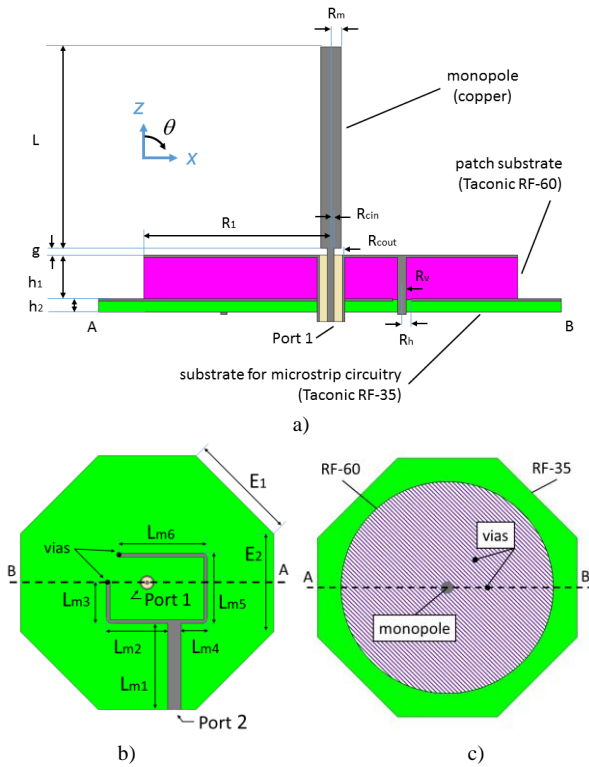


Fig. 1. The proposed antenna: a) cross-section following the AB dashed black line. Thickness of the conducting layers (grey); not to scale; b) bottom view, showing feed circuitry detail; c) top view.

preventing perturbation of the resonant modes. The coaxial inner conductor is connected to the monopole (of length L and radius R_m). For good matching, a section of height g and radius R_{cin} (i.e. same as inner conductor of the coaxial cable) was introduced at this junction. The cable shield (of radius R_{cout}) is connected to the monopole ground plane.

The antenna dimensions are: $L = 28$ mm; $R_m = 1.5$ mm; $R_1 = 26$ mm; $g = 2$ mm, $h_1 = 6$ mm, $h_2 = 1.5$ mm, $R_{cin} = 0.45$ mm, $R_{cout} = 1.5$ mm, $R_v = 0.6$ mm, $R_h = 2$ mm. The dimensions of the feed network are: $L_1 = 21.8$ mm; $L_2 = 15.7$ mm; $L_3 = 10.4$ mm; $L_4 = 6.7$ mm; $L_5 = 18.0$ mm and $L_6 = 22.5$ mm.

III. PRINCIPLES OF OPERATION

Flexible switchless beamforming is achieved by superposition of the radiation from two components: the monopole (excited by port 1) and the patch (excited by port 2). At 2.54 GHz the patch operates in its second resonant mode (seen in Fig. 2), producing radiation in the xy -plane ($\theta = 90^\circ$). Within the patch two orthogonal modes of the same order are excited in phase quadrature. This generates an omnidirectional pattern in the xy -plane, but with the farfield signal phase linearly dependent on angle ϕ (see Fig. 3).

On the other hand, the monopole also produces an omnidirectional pattern, however with a constant phase in the xy -cut. By using superposition between these two sources, one can flexibly rotate the radiation pattern and direct the beam by applying a phase shift between the two ports. The method has multiple advantages over pattern reconfiguration involving switches [1-7]: most notably it can be controlled from a

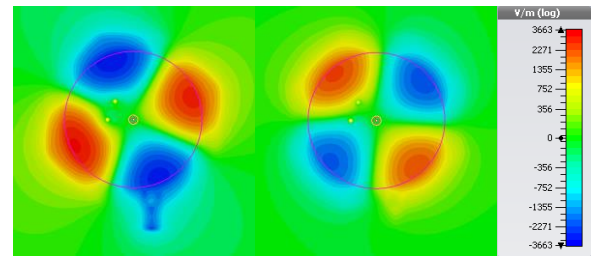


Fig. 2. Electric fields (z -components) in the xy -plane cross-section of the circular patch: phase 180° (left) and 270° (right).

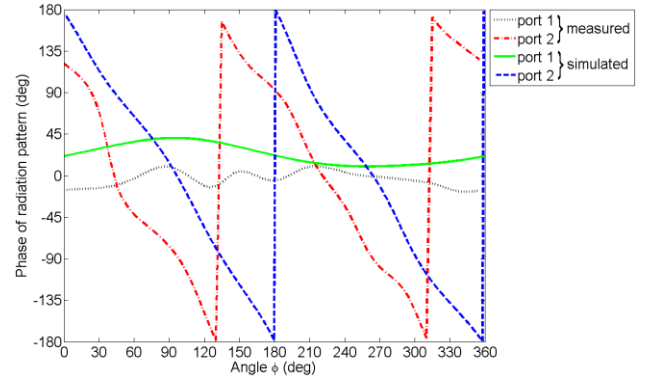


Fig. 3. Phase of the radiation pattern (vertical polarization) in xy -plane at 2.54 GHz, when only one port is excited.

baseband level [10], for which it is even possible to generate multiple patterns at the same time and frequency. As opposed to an antenna array, where the distance is used to generate phase dependency, here the phase is varied by an internal antenna mechanism, allowing size reduction.

The antenna offers comparable functionality to a two-element array, however at a significantly reduced size. E.g. an array using monopoles with comparable ground planes require double the volume of the proposed antenna, mainly due to $\lambda/2$ spacing between radiators. Furthermore, the achievable radiation patterns are much different: an array will produce two beams, symmetrically with respect to a plane passing through both antennas; in the proposed solution the two beams will always be at 180° with respect to each other. Future research may combine these two effects in order to achieve more complex patterns. Finally, the proposed antenna can be further miniaturized simply by increasing the relative permittivity of the circular patch.

IV. MEASUREMENTS

The antenna was prototyped and tested. Fig. 4 shows the S_{11} and S_{22} , measured directly at antenna ports. The isolation is better than 16 and 18 dB in simulation and measurement respectively (not shown for brevity). It can be seen, that the monopole (port 1) is much more wideband than the patch, which is expected from basic antenna theory. The bandwidth for which both ports are matched (i.e. < -10 dB) is from 2.525 to 2.595 GHz. Within this bandwidth the antenna can reconfigure its radiation pattern, as outlined in Section III. However if only omnidirectional performance (without reconfiguration) is required, the antenna can offer an additional bandwidth from 2.235 to 2.725 GHz.

Fig. 5 shows the measured radiation pattern for four phase

shifts (denoted as Δ_{ph}): 0° , 90° , 180° and 270° . The results were obtained using the spherical near field technique at the Institute for High Frequency Technology, RWTH Aachen University. The antenna was placed on a PVC holder with semi-rigid cables providing connection.

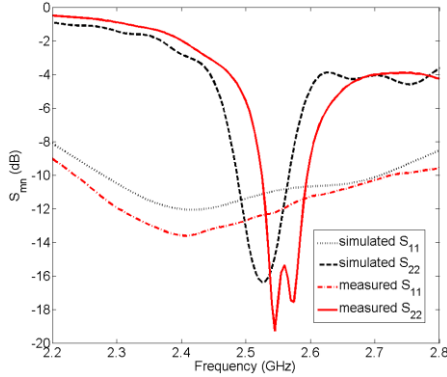


Fig. 4. Measured and simulated S_{11} and S_{22} .

It is shown in Fig. 5a, that the steering in the azimuth (xy -plane) can be realized and is linearly proportional to the phase shift introduced. Some asymmetry can be seen for the $\Delta_{ph} = 90^\circ$ configuration, especially around $\phi = 120^\circ$. This is due to the perturbation from the SMA and semi-rigid cable used to feed port 2. For comparison, Fig. 5c shows the simulated results using CST MWS time-domain solver.

Fig. 5b and 5d show the radiation patterns in the elevation (ϕ -cut) along θ . For each configuration the ϕ -cuts were spaced 45° apart to cover the maximum pattern value for a given Δ_{ph} value. It should be noted that due to small antenna size, the holder and dielectric positioner obstructed radiation for $\theta > 148^\circ$ (marked with grey color in Fig. 5b), hence a strongly perturbed performance around those angles. The other inaccuracy is caused by reflection and radiation from the microstrip phase shifters used to generate the required mode.

Nevertheless, the main energy is radiated in the azimuth plane and a null is seen in the $\theta = 0^\circ$ direction. By comparison, the irregularity is not seen in Fig. 5d, which shows simulated data without the positioner.

Often a disadvantage of beam-switching antennas is decreased efficiency. For fair comparison, Fig. 6 shows the proposed antenna efficiency. The results shown are for the same measurement configuration, including cables and phase shifters. The values are therefore a conservative worst-case measure and are expected to be better in commercial implementation, e.g. due to use of shorter cables. At 2.54 GHz, the measured total efficiencies for $\Delta_{ph} = 0^\circ$, 90° , 180° and 270° are respectively 89%, 86%, 80% and 84%. The maximum realized gains for the respective configurations are 2.5, 2.8, 3.1 and 2.1 dBi. The corresponding simulated values are 3.4, 2.7, 2.7 and 2.3 dBi, which is in reasonable agreement.

V. INDEPENDENT STEERING BETWEEN CHANNELS

One of the key benefits over classical reconfigurable antennas is the ability to steer each frequency channel independently. To demonstrate this, two simple RF transceivers outlined in Fig. 7 were modelled in CST Design Studio [10]. For beam

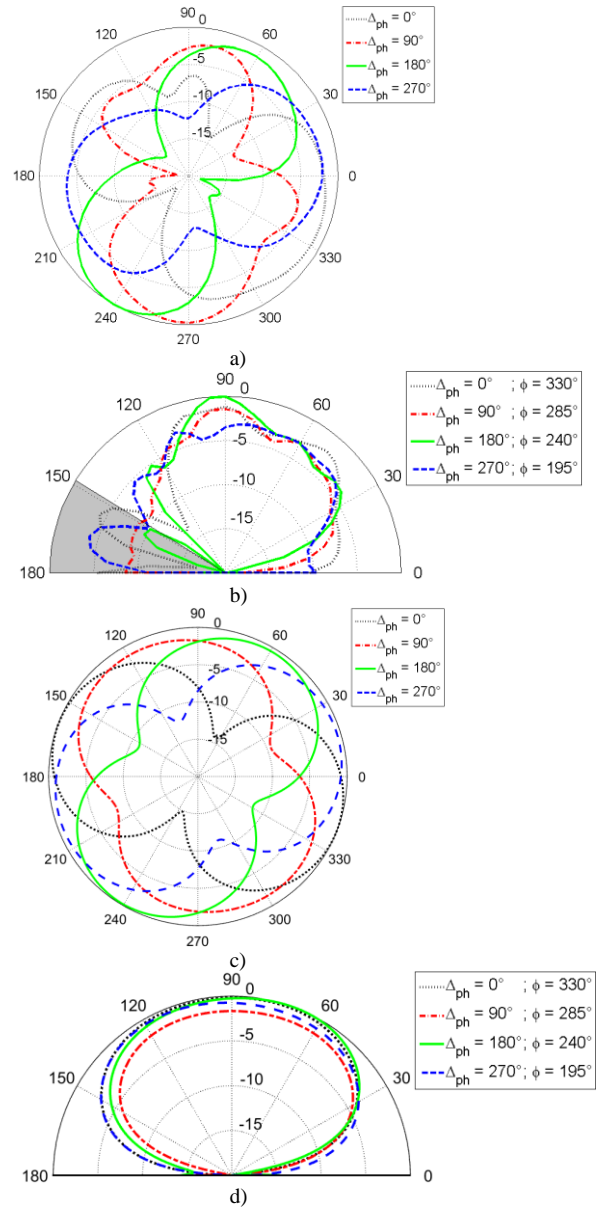


Fig. 5. Simulated normalized radiation pattern (vertical polarization) for various values of Δ_{ph} at 2.54 GHz: a) measured xy -plane; b) measured elevation plane, where the ϕ -cuts are separated by 45° and include the maximum for each Δ_{ph} ; c) simulated xy -plane; d) simulated elevation plane, where the ϕ -cuts are separated by 45° and include the maximum for each Δ_{ph} . steering purposes, each transceiver comprises two IQ-modulators (A and B), each modulator providing a signal for different antenna ports, thus allowing the necessary phase shift. The transceivers operate in adjacent channels (center frequencies 2.54 and 2.55 GHz). Each channel directs the beam in different directions. Passband filters are 9th order Butterworth filters with 10 MHz bandwidth. The modulators were simulated using rat-race couplers with two BAT15 Schottky diodes (diode model provided by Infineon). The I and Q components were controlled using $\pm 8V$.

For the lower channel at 2.54 GHz (left in Fig. 7), both modulators A_1 and B_1 use $(I, Q) = (1; 1)$. This corresponds to $\Delta_{ph} = 0^\circ$ and produces a beam with the maxima at 60° and 240° (while transmitting symbol 11). On the other hand, for the upper channel at 2.55 GHz (right in Fig. 7) modulator A_2

uses $(I, Q) = (+1, +1)$, while $B_2 - (I, Q) = (-1, -1)$. This produced $\Delta_{ph} = 180^\circ$ and yields a beam with maxima at 160° and 340° , i.e. almost orthogonal (100° difference) to the lower channel (while transmitting the same symbol ‘11’). This 10° error is considered to be due to modulator imperfections. Different symbols within a fixed beam can be transmitted by changing signals simultaneously at modulators A and B, while

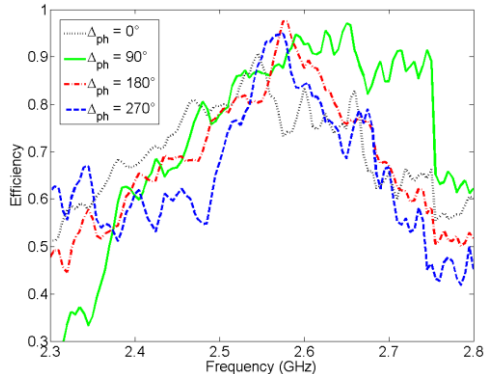


Fig. 6. Measured total efficiency of the proposed antenna.

changing the signal in only one modulator rotates the beam. This is summarized in Table I using 4-QAM modulation.

The normalized radiation patterns are demonstrated in Fig. 8. It can be seen, that the patterns remain stable within the channel bandwidth, with no visible difference between 2.55 GHz and 2.548 GHz., despite the latter being 2 MHz from the edge frequency of 2.545 GHz. This performance is solely dependent on the filters used, i.e. 9th order filters provide around 10 dB attenuation at 2.545 GHz which ensures the two patterns do not interfere. Please note, that the radiation pattern results are normalized and do not account for weaker radiation at 2.545 GHz, which is due to weaker input signal.

It is expected that for the commercial implementation, the filter complexity is no greater than currently used in state-of-

TABLE I
COMBINATION OF (I, Q) COMPONENTS TO TRANSMIT DATA IN GIVEN DIRECTION – EXEMPLARY 4-QAM MODULATION

	$\Delta_{ph} = 0^\circ$		$\Delta_{ph} = 90^\circ$		$\Delta_{ph} = 180^\circ$	
	A_N (I; Q)	B_N (I; Q)	A_N (I; Q)	B_N (I; Q)	A_N (I; Q)	B_N (I; Q)
11	+1; +1	+1; +1	+1; +1	+1; -1	+1; +1	-1; -1
10	+1; -1	+1; -1	+1; -1	-1; -1	+1; -1	-1; +1
00	-1; -1	-1; -1	-1; -1	-1; +1	-1; -1	+1; +1
01	-1; +1	-1; +1	-1; +1	+1; +1	-1; +1	+1; -1

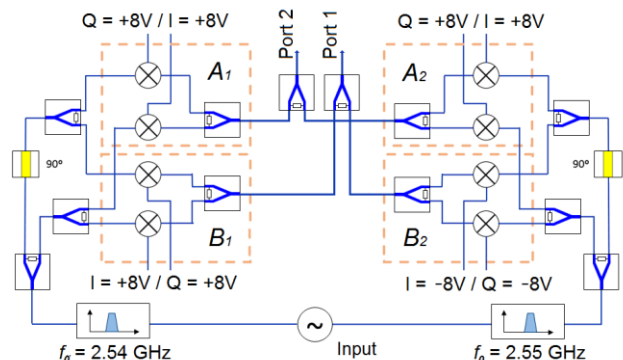


Fig. 7. Circuitry used in CST Design Studio to generate the modulated input signals for the antenna.

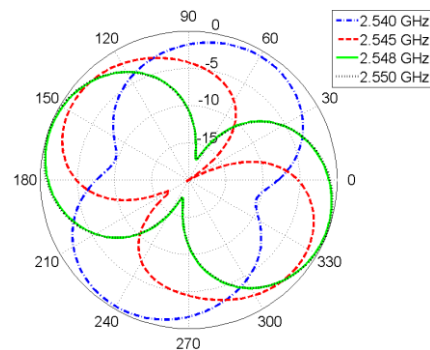


Fig. 8. Normalized radiation patterns in xy -plane including the effect of the feed network shown in Fig. 7.

art antennas, and can be even decreased if an angular separation between neighboring channels is guaranteed. The solution – if implemented as proposed – involves double the amount of mixers, however given the development of RF circuits this does not seem to impede implementation. Another practical issue is synchronization between modulators A and B, as phase noise may cause squint. A relatively broad beam should provide enough margin to preserve communication.

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