On the Efficiency of Miniaturized 360° Beam-Scanning Antenna

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***Abstract*—The efficiency and beam-scanning performance of a compact, beam reconfigurable antenna are presented. The proposed design provides a 360° reconfigurable bidirectional radiation pattern in the horizontal plane by using phase variations between its 3 ports. Antenna miniaturization is achieved by dielectric loading. The miniaturized designs are presented for 4 different permittivity values so that the resonant frequency is shifted from 2.46 GHz to 2.16 GHz, 1.95 GHz and 1.8 GHz. The simulated results show good linear beam-scanning despite a decrease in antenna efficiency.**

***Index Terms*—reconfigurable antenna, beamscanning, antenna miniaturization, dielectric loaded antenna, antenna efficiency**

I. INTRODUCTION

The basic principles of electrically small antennas are well known, with numerous designs available in the literature [1 - 4]. However, most of such designs offer a radiation pattern that is described by only basic spherical modes (either electric or magnetic). This means that the antenna can support only quasi-omnidirectional radiation, without any reconfiguration capability. While omnidirectional pattern, with constant phase for all directions, allows significant miniaturization down to fractions of wavelengths, it is not capable of any beam-steering or MIMO capabilities, as required for modern applications. While basic efficiency limits for omnidirectional electrically small antennas are well established in the literature, few works investigate similar limits for more complex radiation patterns. Since such patterns rely on higher order spherical modes, their efficiency performance will further decrease as compared to the omnidirectional case.

To allow flexible pattern reconfiguration with a compact shape, it was proposed to use a dual-mode antenna, where each mode generates different phase variation in the otherwise omnidirectional pattern [5]. This allows replacement of antenna arrays with much more compact structures. However, reported antenna diameter is ~$\lambda/2$, which is typically not regarded as an electrically small antenna.

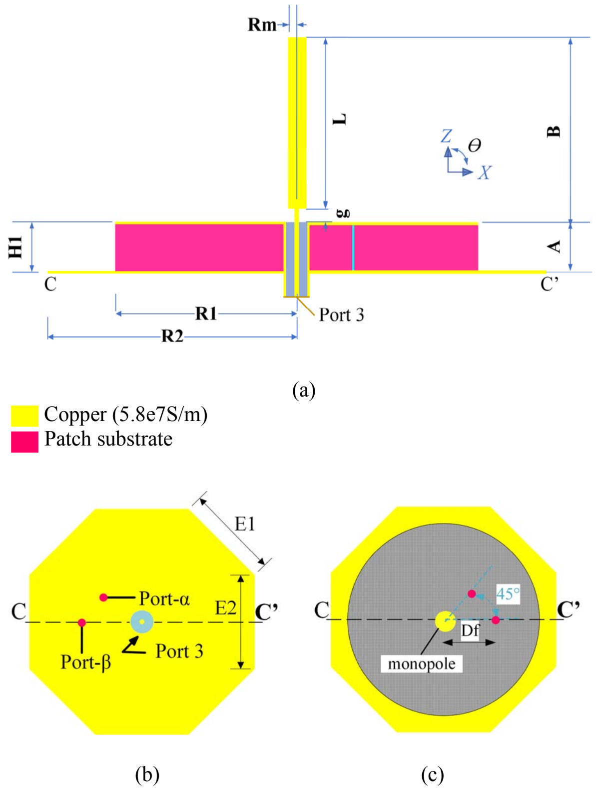
This paper studies the performance of compact beam reconfigurable antenna, where such reconfigurability is achieved by combining three omnidirectional radiation patterns with phase variations along their omnidirectional plane. Since such radiation needs to be described by higher order spherical modes, it is expected that their efficiency will deteriorate more significantly, as compared to similar-sized omnidirectional antennas with fixed patterns. The proposed study aims for the first time to quantify this problem by using numerical simulations. This is done with an antenna utilizing three different modes, each providing omnidirectional coverage with different phase characteristics.

II. ANTENNA DESCRIPTION

A. Antenna

The antenna is depicted in Fig. 1. It is divided into two parts (upper and lower). The main component is a circular patch located in the lower part (A), initially milled with a Taconic RF-60 substrate (relative permittivity $\varepsilon_r = 6$, height = 6.35 mm). For miniaturization analysis, its permittivity is gradually increased from 6 to 12 by two units' steps. The patch operates using two orthogonal TM_{21} resonant modes, fed using two ports [see Fig.1 (c)] oriented 45° with respect to each other. This generates the required two orthogonal TM_{21} modes. The ports are placed at *Df* distance from the center of the disc. Fig.1 (b) shows the location of the ports, denoted as α and β. They provide connections with the feed network discussed in subsection II.B. The ground is of an octagonal shape to ensure symmetry for both TM_{21} modes.

The upper part (B) is a copper quarter-wave monopole, with height *L* and radius *Rm*. It is fed using a 50 Ω semi-rigid coaxial cable, connected to port 3. For a good matching, the copper is lifted with distance *g* above the circular copper plane of radius *R1*. The initial value of the monopole length is $L = 28.5$ mm, however, for miniaturization study, it will be increased to match the changing bandwidth of section (A). This is in order to synthesize the radiation patterns and demonstrate beam-steering capabilities. The changes in the permittivity values and the monopole length are summarized in Table I.



(a)

(b) (c)

Fig. 1. Proposed antenna: (a) cross section following the CC' dashed black line. The thickness of the conducting layers (yellow) not to scale; (b) a bottom view, showing antenna ports; (c) top view.

The overall antenna dimensions are (All in mm): L = 28.5; $E1 = 24.75$, $E2 = 28.5$, Rm = 1.5; $R1 = 25.8$, $R2$ = 31.75; $g = 2$, $H1$ = 6.35 and Df = 10.

B. Feed Network

Fig. 2 depicts the feed network of the proposed antenna. The feeding of the circular patch is executed through a quadrature hybrid coupler connected to two discrete ports α (alpha) and β (betta) located in part (A).

The ports α and β are connected through a standard hybrid coupler to ports 1 and 2, as seen in Fig. 2. The hybrid coupler provides the phase shift of +90° when fed in port 1 and –90° when fed at port 2 [6]. This, when feeding two inputs of the dielectric resonator located in part A, will ensure that the electric field rotates clockwise (when fed at port 1) or counter-clockwise (when fed at port 2). Consequently, it will observe the phase of the electric field changing in two opposite directions, providing beamforming capability of the antenna.

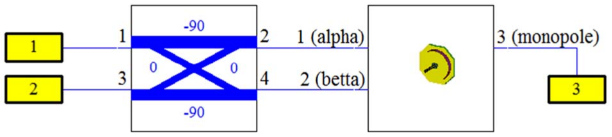


Fig. 2. Feed circuit for the proposed antenna.

TABLE I. ANTENNA PARAMETERS FOR THE EACH OF THE FOUR PERMITTIVITY VALUES

Miniaturization Parameters				
Relative permittivity ε_r	***Monopole length L (mm)***	***Center frequency (GHz)***	$2R_2/\lambda$	***Impedance (Ω)***
6	28.5	2.46	0.52	194
8	33	2.16	0.46	183
10	36.5	1.95	0.41	135
12	39.6	1.8	0.38	91

The power-coupling of the quadrature hybrid coupler is 3 dB. Since the purpose of this study is to investigate the miniaturization capabilities by using different dielectric materials, the input impedance of the antenna will change. To allow a fair comparison, the port impedance *Z1* will change accordingly with permittivity to ensure a good match.

Table I illustrates the antenna dimension ($2R_2$) compared with the observed wavelength at the center frequency for each permittivity variation, along with the values used in subsequent simulations. It is important to note that those values are adjusted to the impedance observed at the frequency with maximum radiation efficiency. This approach ensures that the observed changes in bandwidth and total efficiency are purely due to the radiation effects, not antenna mismatch.

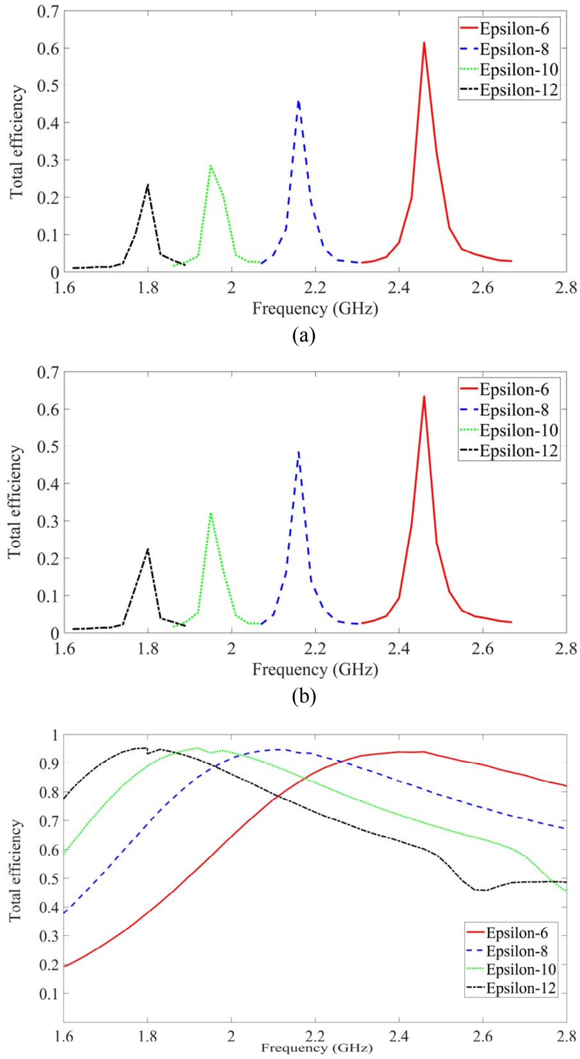
Port 3 of the feed network is connected directly to the port 3 of the antenna, ,i.e., the coaxial line protruding from the antenna's lower part.

III. SIMULATION RESULTS

A. Antenna efficiency

The study of the efficiency of the small reconfigurable antenna, the 3-port antenna structure shown in Section II was modified with different permittivity values, shown in Table I. The impedances of all related components, i.e., interconnecting ports and hybrid coupler, were changed accordingly to adjust changes in antenna's input impedance. The length of the monopole was also adjusted to produce radiation at the same frequency as the other two ports.

For port α the simulated radiation efficiency sharply drops from 61.5% to 46.5%, 33% and 22.5% for the permittivities values 6, 8, 10 and 12 respectively [see Fig. 3(a)]. Similar behavior can be observed for port β [Fig. 3(b)] with its values dropping from 63% to 48%, 34% and 22% as the permittivity is increased from 6 to 8, 10 and 12, respectively. This decrease is expected due to antenna miniaturization. It can be observed that the value is significantly smaller than the efficiency of an omnidirectional antenna of the comparable size. This is due to the necessity for phase variation along the omnidirectional plane and associated higher-order spherical modes. The efficiency of the monopole, which is not subjected to miniaturization, is kept around 94% across all the investigated permittivities [see Fig. 3(c)]. Table II illustrates the scattering parameters results for different permittivity values. An important parameter to be considered for analyzing the antenna total radiated energy is S_{21} / S_{12} which is the coupled energy between ports 1 and 2.



(a)

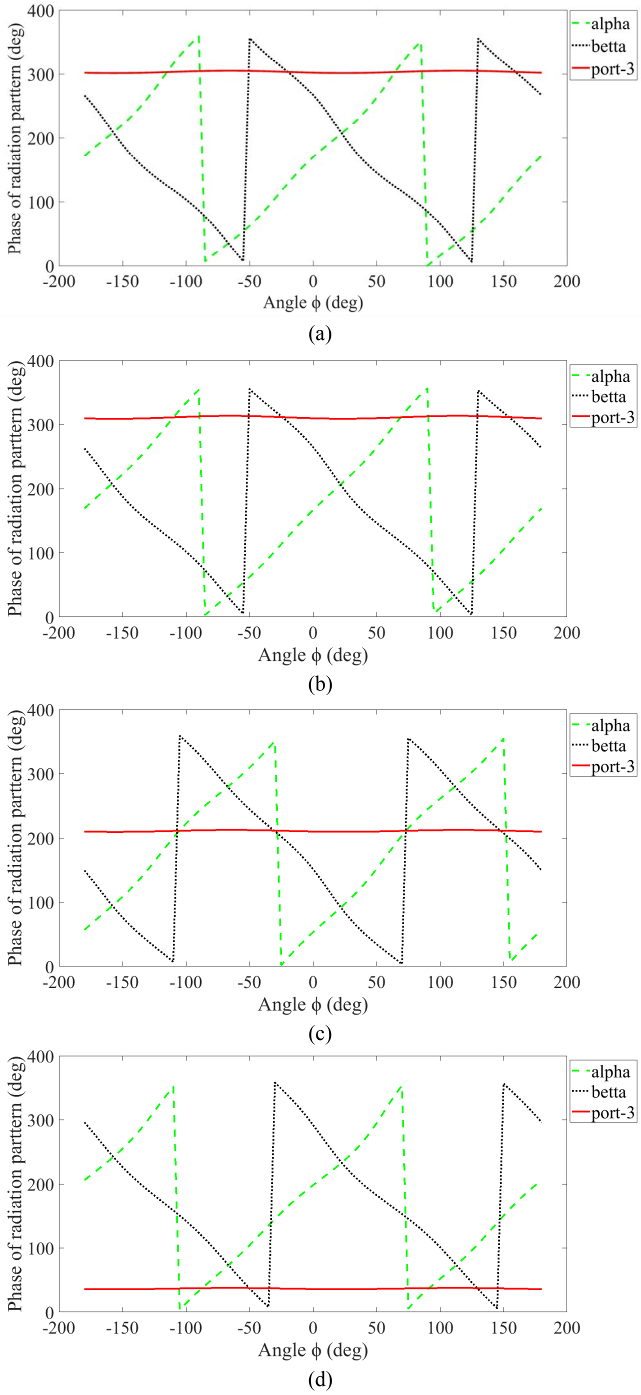
(b)

(c)

Fig. 3. Measured total efficiency of the proposed antenna for different values of permittivity: (a) port α; (b) port β; (c) port 3 - monopole.

TABLE II. SCATTERING PARAMETERS OF THE FOUR ANTENNA MODELS

S-parameters at center frequency (dB)								
ε_r	S_{11}	S_{21}, S_{12}	S_{31}	S_{22}	S_{32}	S_{13}	S_{23}	S_{33}
6	-21	-10	-26	-19	-25	-24	-24	-13
8	-22	-15	-27	-20	-26	-26	-25	-13
10	-24	-26	-28	-19	-27	-26	-25	-13
12	-36	-8	-24	-17	-24	-24	-24	-13



(a)

(b)

(c)

(d)

Fig. 4. Phase of the radiation patterns (vertical polarization) in *xy*-plane: (a) $\varepsilon_r = 6$; (b) $\varepsilon_r = 8$; (c) $\varepsilon_r = 10$; (d) $\varepsilon_r = 12$.

B. *Radiation patterns*

The key enabler for the beam-steering of the proposed antenna is the phase variation along the omnidirectional plane (*xy*-plane) that changes linearly with different ports. The phase is changing linearly with angle ϕ, avoiding the problem of varying beamwidth as in conventional antenna arrays. The monopole provides a constant phase in the whole omnidirectional plane, while the two modes generated by the part (A) change the phase in opposite directions.

Simulated results show that with increased permittivity, the basic phase properties of the antenna's radiation patterns are preserved. Fig. 4 [(a) – (d)] demonstrate similar phase performance within the full range of investigated permittivities.

C. *Beam steering*

To investigate the impact of antenna miniaturization on beamforming, four different beam configurations were generated with main lobes separated by 45°. The applied values of the phase shift between the ports are shown in Table III, which are guided by the phase characteristics shown in section III.B. Despite the decreased efficiency, a linear beamsteering is observed in Fig. 5. For $\varepsilon_r = 6$ the main beams exhibit directivities between 3.11 – 3.76 dBi, with 1.38 – 2.04 dB gain and 62.4°– 66.3° half-power beamwidth. Applying a similar phase shift for higher permittivities, i.e., 8, 10 and 12 produces similar beams (radiation patterns not shown for brevity), i.e., the main beam directions are not affected. However, some changes in the gains are observed, varying from 1.57 – 2.22 dB, 1.71 – 2.18 dB, and 1.69 – 1.96 dB for ε_r=8, 10 and 12 respectively. Directivity changes are 3.62 – 4.26 dBi, 4.46 – 4.88 dBi and 5.14 – 5.29 dBi for ε_r=8, 10 and 12 accordingly. Variations of half-power beamwidth are 64.4° – 65.7°, 67° – 67.9° and 69.5° – 70.3° for ε_r = 8, 10 and 12 correspondingly.

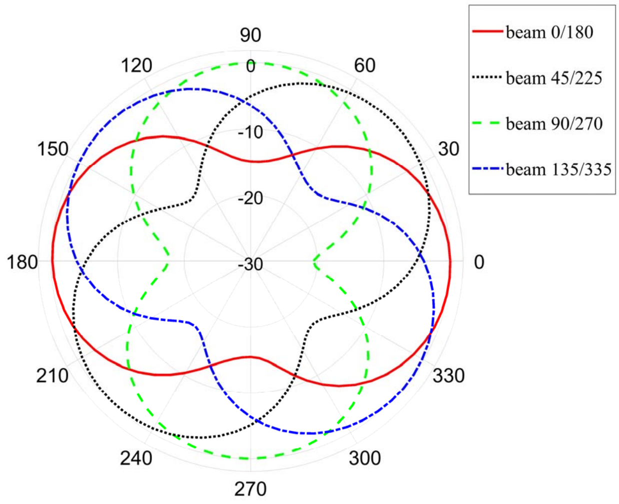


Fig. 5. Synthesized normalized radiation pattern of four beams for ε_r = 12, phase shifts described in Table III.

TABLE III. SUMMMARY OF THE PORTS PHASES IN EACH DIFFERENT BEAMS FOR PERMITTIVITY 12

Beam direction	**Phase shift applied**		
	Port 1	***Port 2***	***Port 3***
0°/180°	0°	–105°	150°
45°/225°	0°	93°	–112°
90°/270°	0°	–92°	–10°
135°/315°	0°	110°	70°

IV. CONCLUSION

The paper studied miniaturization capabilities of a pattern-reconfigurable antenna capable of flexibly rotating a bi-directional radiation pattern within 360°. It offers a significantly simpler design over [7], with two modes integrated into single dielectric resonator and simplified feed structure without the need for a de-coupling network.

It is shown, that the efficiency of the antenna deteriorates as the structure is being miniaturized. While this phenomena is known for electrically small antennas, the drop in efficiency is significantly greater than expected from fixed-pattern omnidirectional electrically small antennas. This is attributed to the presence of higher spherical modes, which are needed to diversify the phase and achieve beamsteering.

Despite the efficiency drop, the phase properties of the radiation patterns are little affected, and the antenna offers the same beamsteering capabilities.

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