Asymmetric-Circular Shaped Slotted Microstrip Antennas for Circular Polarization and RFID Applications

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***Abstract*—Novel asymmetric-circular shaped slotted microstrip patch antennas with slits are proposed for circularly polarized (CP) radiation and radio frequency identification (RFID) reader applications. A single-feed configuration based asymmetric-circular shaped slotted square microstrip patches are adopted to realize the compact circularly polarized microstrip antennas. The asymmetric-circular shaped slot(s) along the diagonal directions are embedded symmetrically onto a square microstrip patch for CP radiation and small antenna size. The CP radiation can be achieved by slightly asymmetric (unbalanced) patch along the diagonal directions by slot areas. Four symmetric-slits are also embedded symmetrically along the orthogonal directions of the asymmetric-circular shaped slotted patch to further reduce antenna size. The operating frequency of the antenna can be tuned by varying the slit length while keeping the CP radiation unchanged. The measured 3-dB axial-ratio (AR) bandwidth of around 6.0 MHz with 17.0 MHz impedance bandwidth is achieved for the antenna on a RO4003C substrate. The overall antenna size is $0.27\lambda_o \times 0.27\lambda_o \times 0.0137\lambda_o$ at 900 MHz.**

***Index Terms*—Circular polarization (CP), circularly polarized antenna, microstrip antenna, radio frequency identification (RFID), slotted patch, UHF.**

I. Introduction

THE radio frequency identification (RFID) system in the ultra high frequency (UHF) band has gained popularity in many applications, as it provides longer readable range and fast reading speed [1]. RFID technology relates to the short-range wireless communications and uses the radio frequency to read certain information from a device (tag). The RFID system consists of the reader and the tag. Commonly, the UHF tag antennas are linearly polarized. Because of the random orientation of the tags in actual application scenarios, a circularly polarized antenna for the RFID reader is required to get a most efficient UHF RFID system. The commercial use of the UHF RFID system in logistics, and supply chain management has become very popular, which has made compact handheld reader units become more and more important.

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The reader antenna is one of the important components in the RFID system. Circularly polarized microstrip antennas (CPMAs) can reduce the loss caused by the multipath effects between the reader and the tag antenna. Frequencies specifically that have been reserved for the ISM (industrial, scientific, medical) bands can be used for the RFID applications. Due to the merits of high data transfer rate and broad readable range, passive RFID systems at the UHF band are preferred in many applications. The total frequency span of the UHF band used for RFID systems is 840–960 MHz. However, there is not a UHF range accepted worldwide for the RFID applications. The system operates at the bands of 902–928 MHz in America, 865–867 MHz in Europe, and 840–955 MHz in Asia-Pacific region. In Asia-Pacific region, the UHF RFID frequency range is different in different countries: China (840.5–844.5 MHz, 920.5–924.5 MHz), Japan (952–955 MHz), India (865–867 MHz), Hong Kong (865–868 MHz, 920–925 MHz), Taiwan (920–928 MHz), Korea (908.5–910 MHz, 910–914 MHz), Singapore (866–869 MHz, 923–925 MHz), Australia (920–926 MHz), etc. As a result, except the America UHF RFID frequency-band, in other countries UHF RFID allocation bandwidths are between 3 to 6 MHz. The broadband CPMA designs to cover total frequency span of the UHF band for RFID applications have been reported [2], [3]. The sizes of the broadband CPMAs are bulky and not suitable for handheld or portable reader applications.

The single-feed CPMAs are usually more compact as compared to the dual-feed CPMAs [4]. The major consideration for the CP microstrip antenna design of handheld/portable RFID reader applications is overall compact size of the antenna; the antenna gain and bandwidth are not so critical. However, the antenna must cover at least one UHF RFID band with bandwidth of few MHz. The small size of the CPMA can be achieved at the cost of limited gain, narrow 3-dB AR bandwidth and impedance bandwidth. Various techniques have been published [5]–[10] to generate the CP radiation of the single-feed microstrip antennas.

The single-feed square patch was proposed by Sharma and Gupta for CP radiation using the symmetric truncated corners method [5]. The single-feed CP annular-ring, square and circular patch antennas with perturbation elements (symmetric cross, inner stubs techniques etc.) have been reported in [6]–[10]. The study of the asymmetric-circular shaped slotted microstrip patches (ACSSMPs) for the CP radiation has not been published in open literature.

In this paper, novel CP ACSSMP antennas are proposed for the UHF RFID handheld reader applications. An ACSSMP an-

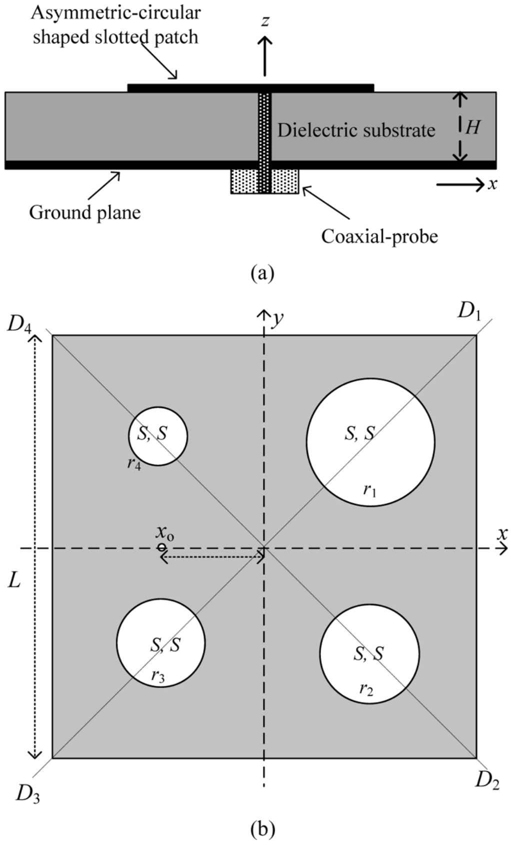


Fig. 1. (a) Cross-section view of the proposed antenna. (b) Asymmetric-circular shaped slotted microstrip patch.

tenna with slits gives a compact antenna configuration. A new asymmetric-circular shaped slotted square patch is used to generate a CP radiation with compact antenna size. By slightly varying the radius of the circular-slots in diagonal directions of a square patch, CP radiation of the antenna can be obtained. The symmetric-slits are embedded along the orthogonal directions on the ACSSMP for further size reduction of the microstrip antenna. In addition, the slits can also be used for tuning of the operating frequency-band. The CP ACSSMP antenna with slits is designed, fabricated and tested. The measured results are compared with simulated results obtained from the IE3D commercial simulator [11].

II. Asymmetric-Circular Shaped Slotted Patch Antenna and Design

The cross-section view of the proposed asymmetric-circular shaped slotted (unbalanced) square microstrip patch antenna is shown in Fig. 1(a). Length of the square patch is L (78.0 mm) and ground-plane size of the antenna is 90.0 mm × 90.0 mm. x_o is the coaxial feed-location from the patch center. The overall antenna size is designed based on the handheld/portable RFID reader requirements.

The proposed CP ACSSMP is shown in Fig. 1(b). For CP radiation, proposed ACSSMP has to support two orthogonal resonance modes with a 90° phase shift. The orthogonal modes are excited by asymmetries along the axis of a patch using the circular slots at 45° to the feed-location axis. The ACSSMP is proposed for the CP radiation with size reduction of the antenna.

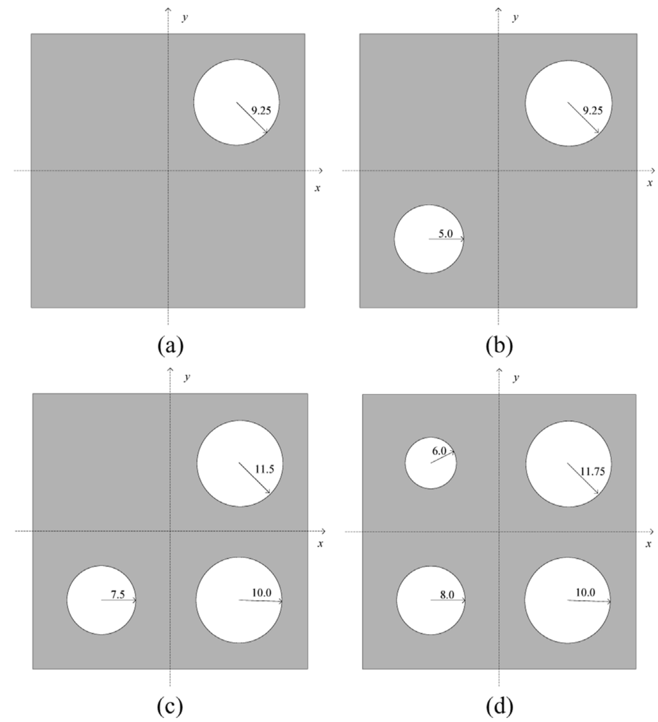


Fig. 2. Examples of the ACSSMP (a) one circular-slot, (b) two circular-slots, (c) three circular-slots, (d) four circular-slots.

The locations of four unequal circular-slots (r_i, $i = 1$ to 4, where r_i is radii of circular-slots) are located symmetrically at $S, S = L/4$ along the diagonal directions (D_i) from center of the square patch as shown in Fig. 1(b). The coaxial feed-location is on the x-axis and it is 45° from the asymmetries by the circular-slots on the patch radiator. By slightly changing radii of the slot(s) in diagonal directions, the CP radiation can be obtained. The relation of the circular-slot radii on the patch should be $r_1 > r_2 > r_3 > r_4$ (four circular-slots) or $r_1 > r_2 > r_3$ (three circular-slots) or $r_1 > r_3$ (two circular-slots) or $r_1 > 0$ (one circular-slot). In addition, the slotted patch radiator is also useful for the antenna size reduction.

III. Asymmetric-Circular Shaped Slotted Microstrip Patch Examples

In this section, the ACSSMP antennas are studied and compared. The proposed slotted square microstrip patch antenna with slits is fabricated on a RO4003C substrate (thickness, $H = 4.572$ mm, dielectric constant $= 3.38$ and loss tangent $= 0.0027$). Four examples of the ACSSMPs are illustrated in Fig. 2(a)–(d). The structural dimensions in mm are shown on the patch sketches. The locations (S, S) of the circular-slot(s) are selected symmetrically from the patch center at $S = 19.5$ mm $(L/4)$. The coaxial feed-location is on the x-axis at a distance of 15.0 mm from the slotted square patch center.

A circular-slot is embedded in one of the diagonal directions (D_1) as shown in Fig. 2(a). The radius $(r_1 > 0)$ of the circular-slot is optimized for CP radiation. The two unequal circular-slots (r_1 and r_3) are embedded in diagonal directions D_1 and D_3 respectively as shown in Fig. 2(b). For CP radiation in this case, the relation between two circular-slot radii should be $r_1 > r_3$. The three unequal circular-slots can also be embedded for the CP radiation as shown in Fig. 2(c). The relation between slot radii should be $r_1 > r_2 > r_3$ for CP radiation of the antenna. A group of four unequal circular-slots (r_i) are embedded symmetrically along the diagonal directions (D_i). The radii $(r_1 > r_2 > r_3 > r_4)$ of the slots are optimized for CP radiation. Fig. 2(d) shows four unequal slots based ACSSMP.

The simulated return loss, boresight AR and boresight gain of the four examples are plotted in Fig. 3(a)–(c), respectively. It is found that the resonance frequency of the ACSSMP antenna decreases with increase of slotted area on the patch radiator. As a result, the antenna size is reduced. The operating frequency also decreases with increase number of circular-slots on the patch.

The minimum AR frequency also decreases with increase in number of unequal slots or increase in slotted area on the patch radiator as shown in Fig. 3(b). The boresight gain slightly decreases with increase in the slotted area on the patch radiator. This is due to decrease in electrical antenna size with increase in slotted area on the patch. The slotted area can be increased with four unequal circular slots in diagonal directions of the square patch.

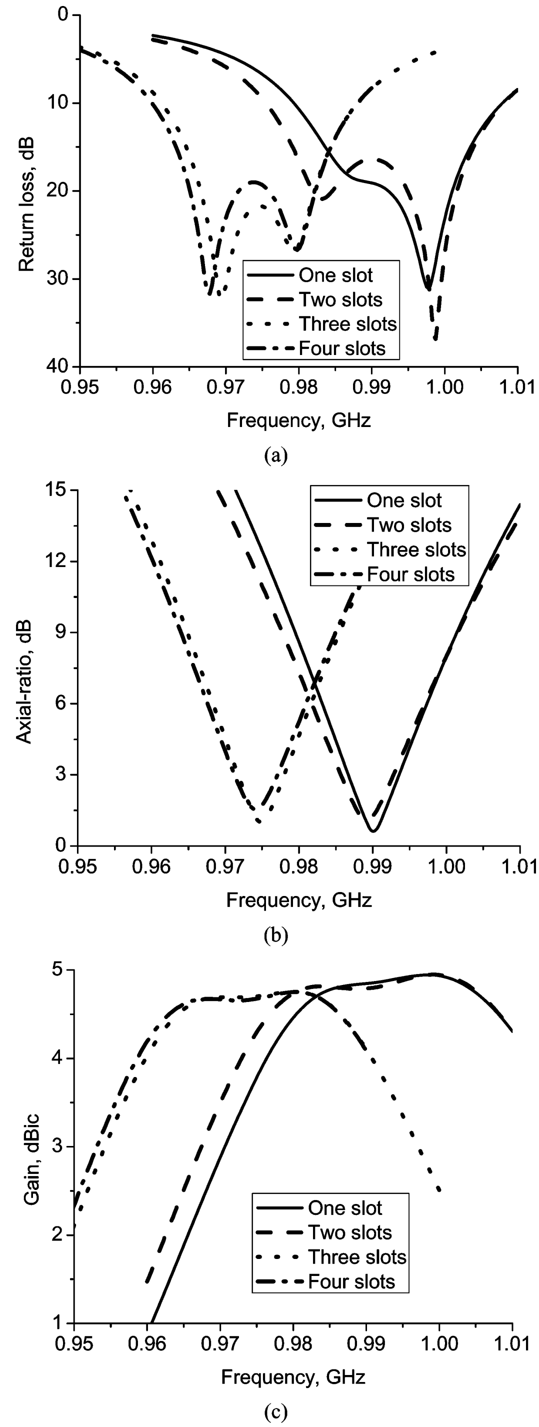


Fig. 3. Simulated results of the ACSSMP antennas: (a) return loss, (b) axial-ratio at the boresight, (c) gain at the boresight.

IV. ACSSMP Antenna With Slits

To further reduce the size of antenna, symmetric-slits are embedded along the orthogonal directions on the ACSSMP (Fig. 2(d)) for the RFID handheld reader applications. Our aim is to design of a single-feed compact CPMA at around 900 MHz for the UHF RFID handheld reader applications. The s_w and s_l are slit width and slit length respectively. The four slots based ACSSMP with slits is illustrated in Fig. 4(a). The optimized circular-slots radii (r_i) are $r_1 = 11.75$ mm, $r_2 = 10.0$ mm, $r_3 = 8.0$ mm and $r_4 = 6.0$ mm respectively. The width $(s_w = 1.0$ mm$)$ and length $(s_l = 16.0$ mm$)$ of the slits are optimized for the operating frequency of the antenna at around 900 MHz. The square patch and the CP truncated corners square patch radiators [5] are shown in Fig. 4(b) and (c) respectively for comparison. The conventional truncated corners square patch is also designed and optimized for CP radiation. The optimized truncated corner length (d) is 8.25 mm. The feed-location for this antenna is $x_o = 15.0$ mm.

A. Comparison of CP Microstrip Patch Antennas

In this section, simulated results of the square patch antenna, CP truncated corners square patch antenna, proposed CP ACSSMP with and without slits (Fig. 2(d)) antennas are compared with a fixed ground-plane and square patch radiator sizes. The simulated return losses of the antennas are plotted in Fig. 5(a). The square patch antenna resonance frequency is around 1.0 GHz. However, the conventional truncated CP corners patch antenna resonance frequency is around 1.01 GHz. The truncated patch antenna resonance frequency is highest as compared to other antennas. As a result, the truncated corners method did not provide any size reduction of the patch antenna for CP radiation. So it can be concluded that truncated corners method is not useful for compact CPMA designs. The ACSSMP antenna resonance frequency is around 0.97 GHz. The ACSSMP antenna resonance frequency is lower as compared to the square patch antenna and the truncated corners patch antenna. This is due to meandering of the surface current path on an ACSSMP radiator. Accordingly, resonance frequency of the antenna is shifted down. The slits can also be used for further size reduction of the antenna. The ACSSMP antenna with slits resonance frequency is lowest and it is around 0.907 GHz. With fixed ground-plane and patch sizes, the slotted patch antenna with slits is electrically smallest. The slit length also can be used to tune operating frequency of the patch antenna for the desired frequency-band.

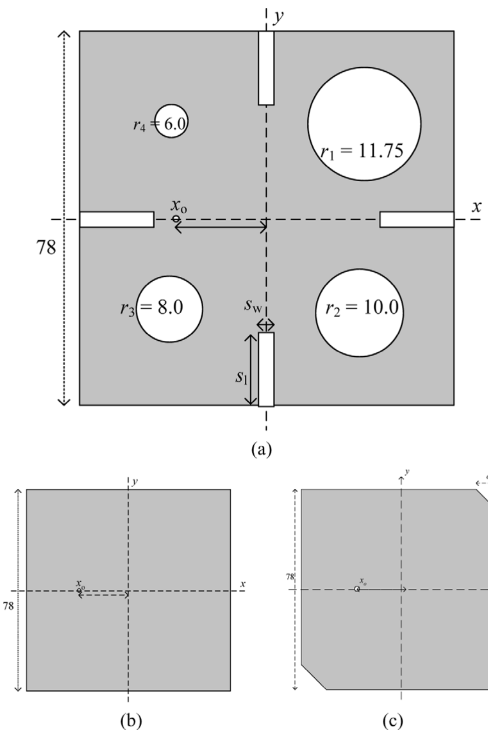


Fig. 4. Square patch radiators: (a) proposed ACSSMP with slits, (b) square patch, (c) truncated corners square patch.

The simulated AR at the boresight of the antennas is plotted in Fig. 5(b). The minimum AR frequencies are around 0.909 GHz, 0.974 GHz and 1.007 GHz for the ACSSMP antenna with slits, ACSSMP antenna and truncated corners patch antenna, respectively. It is to be noted that the square patch antenna is linear polarized $(\mathrm{AR} > 40\ \mathrm{dB})$. The minimum AR frequency is lowest for the ACSSMP with slits antenna. The conventional truncated corners patch, proposed ACSSMP antennas with and without slits show good CP radiation. Fig. 5(c) shows the gain at the boresight of the antennas. The gain of the conventional truncated corners patch radiator and the square patch antennas is a little bit larger compared to the proposed slotted patch antennas. This is due to electrically larger size of the truncated corners patch and the square patch antennas. Note that the slotted patch radiator with slits has lowest gain $(\sim 4.0\ \mathrm{dBic})$.

B. Variation of Symmetric-Slit-Length (s_l) of ACSSMP

In this section, the effects of varying the length (s_l) from 14.0 mm to 17.0 mm are studied. The resonance frequency decreases with increase in the slit length as shown in Fig. 6(a). By changing the slit length, the antenna can easily be optimized to the center of the desired frequency-band. Fig. 6(b) shows the variation of AR at the boresight with slit length. The minimum AR frequency also decreases with increase in slit length. It is found that the CP radiation is not degraded with variation of the slit length. This is very useful because CP radiation (minimum AR) frequency also decreases in the same way as operating resonance frequency with increase in slit length. Accordingly, frequency at which maximum boresight gain is slightly decreases with increase in the slit length. The variation of boresight gain with respect to frequency of the antennas is plotted in Fig. 6(c).

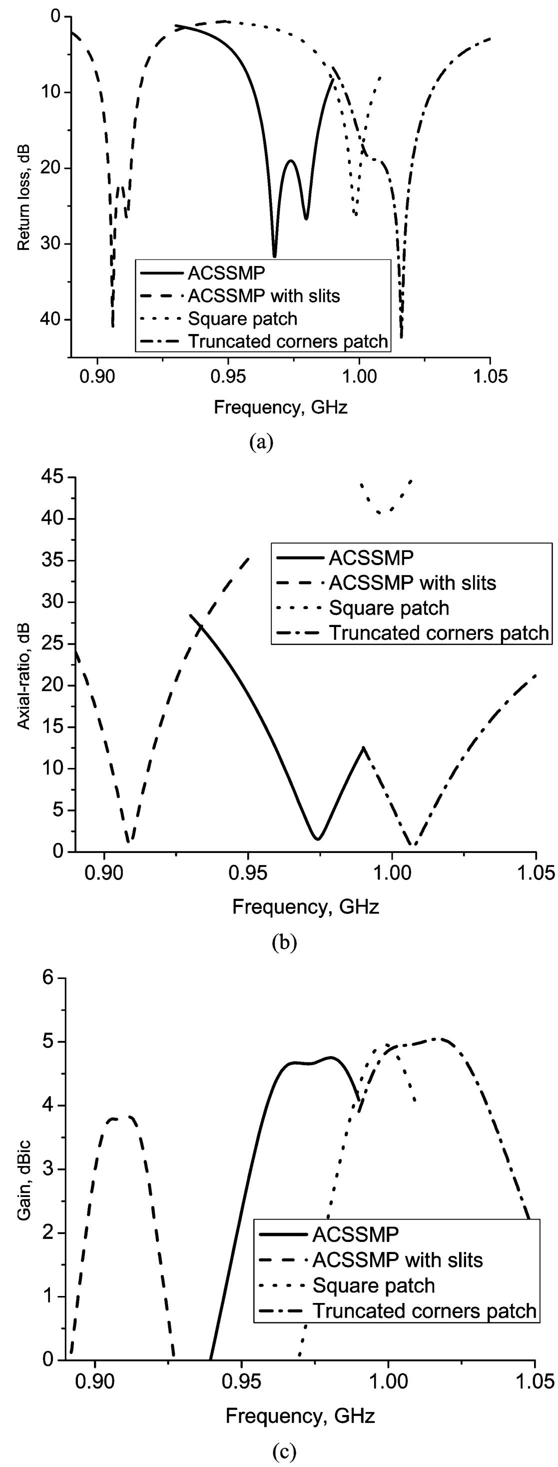


Fig. 5. Simulated antennas performances: (a) return loss. (b) axial-ratio at the boresight, (c) gain at the boresight.

The slit length can be used to tune the operating frequency of the antenna while keeping good CP radiation. However the other antenna parameters are fixed.

C. Results and Discussions

The proposed four slots based ACSSMP antenna is optimized at around 900 MHz UHF band using slit length (s_l) of 16.0 mm. The antenna is linear polarized radiation, when circular slot radii $(r_1 = r_2 = r_3 = r_4)$ are equal. For CP radiation

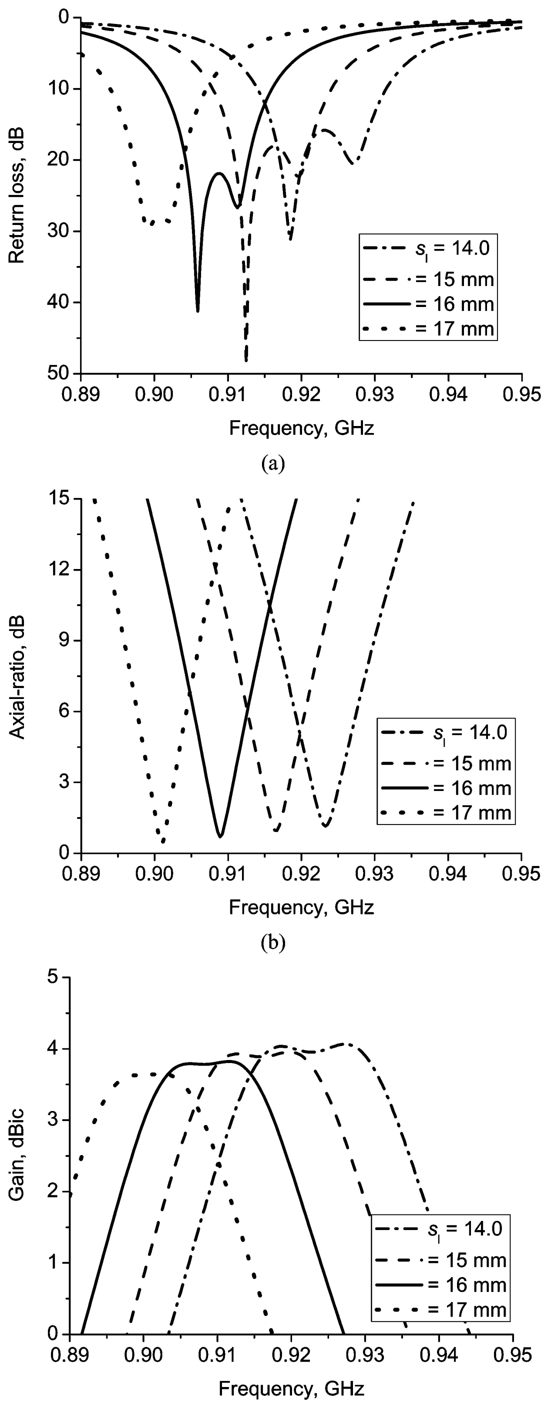


Fig. 6. Variation of slit length: (a) return loss, (b) axial-ratio at the boresight, and (c) gain at the boresight.

the relation between radii of the circular-slots should be unequal $(r_1 > r_2 > r_3 > r_4)$. The current distribution on the ACSSMP radiator with slits is shown in Fig. 7. The strongest current distribution is around the farther end of the slits and around the unequal circular-slots. The four unequal circular-slots and the slits on the radiating patch can cause meandering of the excited surface current paths. Accordingly, resonance frequency of the antenna is lowered as compared to the square patch without slots and slits. So the electrical size of the antenna is reduced.

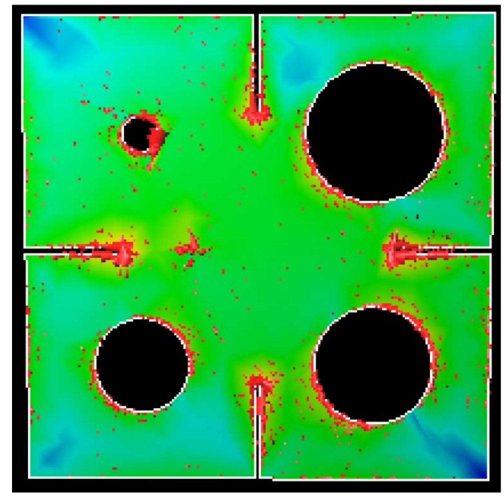


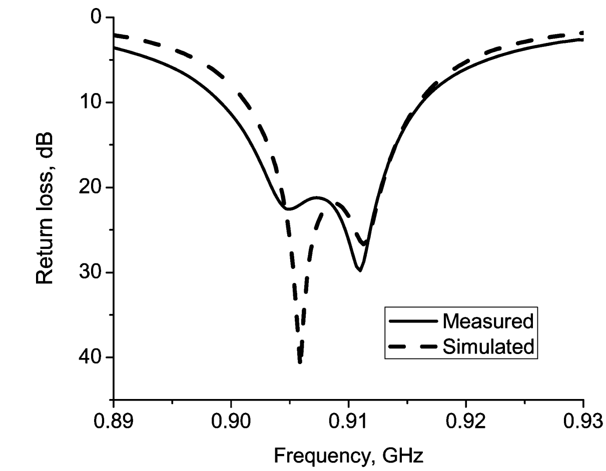
Fig. 7. Current distribution on four slots based ACSSMP radiator with slits at 0.907 GHz.

The proposed antenna design was fabricated and tested to validate the simulated results. The measured and simulated results of return loss, AR at the boresight and gain at the boresight are plotted in Fig. 8(a)–(c) respectively. The measured 10-dB return loss bandwidth is 17.0 MHz (899–916 MHz) and the simulated bandwidth is 15.0 MHz (901–916 MHz). The good agreement is observed between simulated and measured return loss results. The measured 3-dB AR bandwidth is more than 6.0 MHz (904–909 MHz) and it is within the measured 10-dB return loss bandwidth. The simulated 3-dB AR bandwidth is more than 5.0 MHz (907–911 MHz). The agreement of the simulated and measured 3-dB AR bandwidth is good. The measured 3-dB AR bandwidth is able to cover one RFID UHF band. The measured maximum boresight gain is 3.7 dBic at 906 MHz. The gain remains relatively constant around 3.5 dBic with variation of less than 0.2 dB within the 3-dB AR bandwidth. The simulated gain at the boresight is slightly higher than the measured gain values.

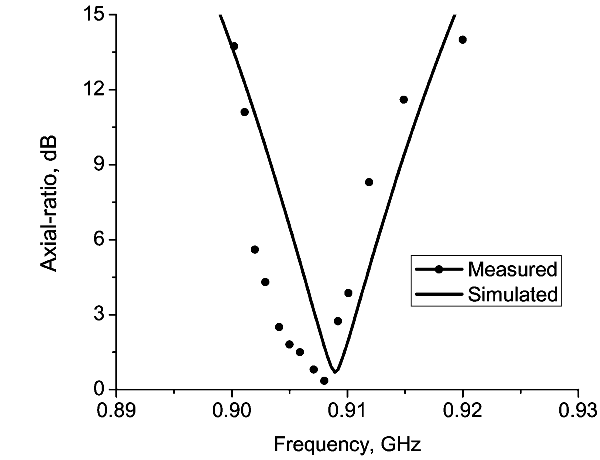
The radiation patterns of the antenna were measured with a rotating linear polarized transmitting horn antenna for the x-z and y-z principal planes. Fig. 9(a) and (b) show the measured normalized radiation patterns at 904 MHz and 908 MHz, respectively, in the x-z and y-z planes. The 3-dB AR beamwidth is more than 100° for both principal planes (x-z and y-z). The proposed antenna is compact and has wide beam CP radiation. The antenna can be useful for the UHF RFID handheld readers.

V. ACSSMP Antenna With Slits on FR4 Substrate

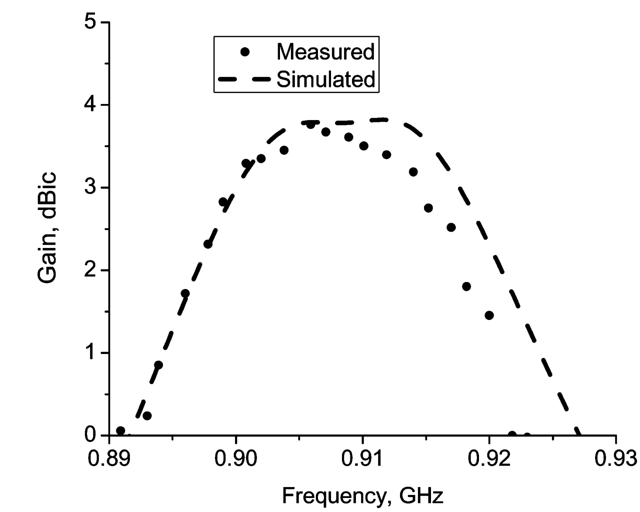
In this section, the circularly polarized two slots based ACSSMP antenna fabricated on an FR4 substrate (thickness, $H = 4.8$ mm, dielectric constant $= 4.3$ and loss tangent $= 0.02$) for the low-cost antenna design is presented. The example of two circular-slots based ACSSMP (Fig. 2(b)) is used with slits for the compact CP antenna design. This antenna is also designed for the handheld RFID reader applications. The designed and optimized antenna dimensions are; $L = 72.0$ mm, ground plane size $= 90.0$ mm $\times$ 90.0 mm, $r_1 = 12.0$ mm, $r_3 = 5.0$ mm, coaxial feed-location $(x_o) = 17.0$ mm, $s_l = 10.0$ mm, and $s_w = 4.0$ mm. The designed antenna on the FR4 substrate also



(a)



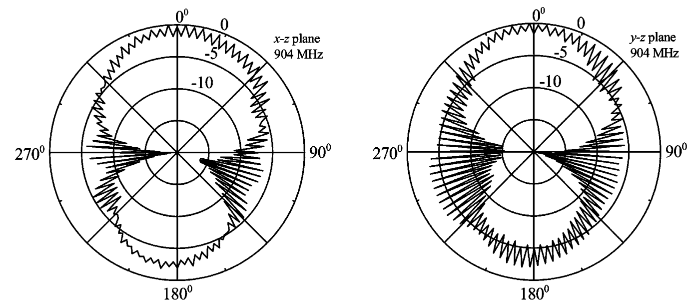
(b)



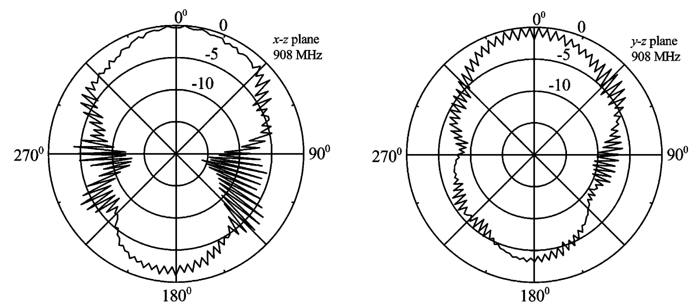
(c)

Fig. 8. Simulated and measured results of the antenna: (a) return loss, (b) axial-ratio at the boresight, and (c) gain at the boresight.

was fabricated and tested. The measured 10-dB return loss bandwidth is 4.01% (904–941 MHz) with 1.2% or 12 MHz (918–929 MHz) 3-dB AR bandwidth. The 3-dB AR beamwidth is more than 100° same as the antenna on a RO4003 substrate. The antenna on a FR4 substrate has larger 3-dB AR bandwidth as compared to the antenna on a Rogers RO4003C substrate. However the gain of the antenna on a FR4 substrate is lower ($\sim 0.5\,\mathrm{dBic}$). The overall antenna sizes are almost same for both substrates.



(a)



(b)

Fig. 9. Measured radiation patterns of the antenna: (a) 904 MHz and (b) 908 MHz for both planes (x-z and y-z planes).

A. Comparison of the CP RFID Reader Antennas

The proposed ACSSMP antenna sizes and measured performances are compared with some commercially available RFID CP reader antennas in Table I. The commercially available reader antennas are bulky and not suitable for the RFID handheld reader applications. However, the commercial CP reader antennas are broadband with higher gain. Moreover the proposed compact CP antennas have wide 3-dB AR beamwidth (100°) as compared to the commercially available CP reader antennas.

B. RFID Tag Reading Range Measurement

To validate the proposed antennas for the RFID reader applications, the tag reading-range were measured for the proposed antennas on RO4003C and low-cost FR4 substrates. The MP9320 2.8 EPC UHF reader and home made UHF tag were used for the measurement of the reading range. The reading range indicates maximum distance of the tag from the reader antenna, where the tag can be detected properly by the handheld RFID reader. The measurement was conducted at the boresight, 30° and 45° offset from the boresight of the antenna. The maximum reading range of 65–70 cm is achieved at the boresight and 63–68 cm is achieved at the directions of around 30° and 45° offset from the boresight for the antenna on RF4 substrate. The maximum tag reading range at the boresight is about 92–96 cm for the antenna on a RO4003C. The reading range for the antenna on a Rogers RO4003C substrate is larger as compared to the antenna on a FR4 substrate. Because the antenna on a RO4003C substrate has higher gain compared to the antenna on an FR4 substrate.

TABLE I
CIRCULARLY POLARIZED UHF RFID READER ANTENNAS

Manufacturer/ Product Name/ID	Electrical Specifications			Mechanical Specifications
	Frequency Range(M Hz)	Gain (dBic)	3-dB Beam Width	Dimensions L x W x H in mm^3
Alien/ ALR-9611-CR [12]	890 - 930	6.0	40°	284.0 ×195.0 × 43.0
Intermec/ IA33A [13]	902 - 928	7.0	65°	259.0 × 259.0 × 38.0
Motorola/ AN200 [14]	900 - 928	6.0	60°	282.0 × 282.0 × 48.3
Motorola/ AN480 [14]	865 - 956	6.0	65°	259.1 × 259.1 × 33.5
Poynting Antennas/PAN L-A0011 [15]	860 - 930	4-5	55°	250.0 × 150.0 × 20.0
MTI/ MT-262014/NRH [16]	902 - 928	7.0	50°	540.0 × 470.0 × 220.0
Gao RFID Inc/326005 [17]	902 - 928	7.5	70°	190.0 × 190.0 × 30.0
ThingMagic/ ANT-NA-2CO [18]	902 - 928	8.0	60°	500.0 × 200.0 × 30.0
Proposed Antenna/ FR4	918 - 929	0.5	100°	90.0 × 90.0 × 4.8
Proposed Antenna/ RO4003C	903 - 909	3.8	100°	90.0 × 90.0 × 4.6

VI. CONCLUSION

Novel asymmetric-circular shaped slotted square microstrip patch antennas with slits have been presented for the CP radiation and UHF RFID handheld reader applications. Two examples of the ACSSMP with slits have also been demonstrated for the UHF RFID handheld readers on Rogers RO4003C substrate and low cost FR4 substrate. The antenna on a RO4003C substrate has a higher gain as compared to the antenna on a FR4 substrate. It has been shown that by changing slit lengths along the orthogonal directions the operating frequency-band of the antenna can be tuned with good CP radiation. The antennas have wide angle CP radiation of around 100°. The proposed ACSSMP antennas are compact and these can be conveniently used in applications such as in handheld/portable UHF RFID readers.

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