Helical Antenna for Handheld UHF RFID Reader

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***Abstract*— In this paper, we describe a compact high gain circularly polarized antenna for handheld UHF RFID reader. The antenna is an axial mode helix operating in a backfire mode with ground plane on top and reflector on the bottom. The described antenna has small footprint (85 mm in diameter) and delivers maximum linear gain > 6 dBil, standing wave ratio < 2, and axial ratio < 2 dB in 60 MHz band centered around 895 MHz (approximate bandwidth 7%). The antenna can be easily tuned to cover any desired portion of the global UHF RFID band (860-960 MHz). The antenna is an attractive solution for handheld readers to maximize tag read range while providing circular polarization. We also review existing antenna solutions for handheld readers and discuss link budget and forward and reverse link tradeoffs.**

I. INTRODUCTION

Most passive UHF RFID tags in the market today are linearly polarized dipoles. Because their orientation is not known in advance, a circularly polarized RFID reader antenna is generally required for various environments where omnidirectional tag reading is desired. To maximize tag read range, high gain antennas (to radiate maximum allowable power) are typically used.

Let us illustrate a relationship between the tag read range and the reader antenna gain. Equivalent Isotropic Radiated Power ($EIRP$) radiated by the reader in the tag direction is:

$$EIRP = P_t G_t \ , \tag{1}$$

where P_t and G_t are the reader power and the realized gain of the transmitting antenna. Assuming that the reader has a good sensitivity (is able to read the tag at any distance as long as it is powered up) and that the tag antenna polarization matches the reader antenna polarization, the tag read range in free space can be found using a well-known formula:

$$r = \frac{\lambda}{4\pi}\sqrt{\frac{EIRP}{P_{tag}}} \ , \tag{2}$$

where λ is wavelength and P_{tag} is the tag sensitivity. Relationship given by equation 2 is illustrated in Figure 1 for two tags: one with -10 dBm sensitivity (state of the art ten years ago, many legacy tags on the market still have similar sensitivity) and -20 dBm sensitivity (current state of the art). It is assumed in both cases that the tag IC is perfectly matched to 2 dBi dipole-type antenna. Every additional 3 dB of reader antenna gain increase the tag range approximately by 40%.

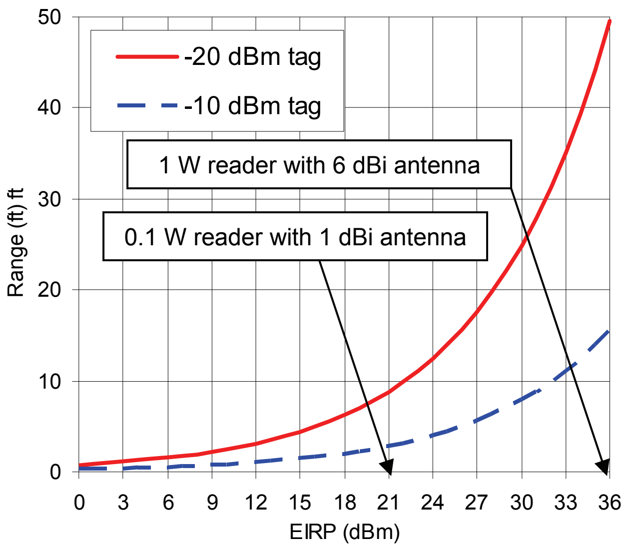

Fig. 1. Relationship between tag read range in frees space and reader EIRP for tags with -10 dBm and -20 dBm receive sensitivity.

While antennas for fixed reader installations can be relatively large (for example, the antenna described in [1] has a fotprint 8.25”x8.25” and the antenna described in [2] has a footprint of 10”x10”), antennas for handheld RFID readers must be compact and ergonomically appealing. Making a compact high gain circularly polarized antenna is a challenging task. Most handheld readers use linearly polarized antennas or patch antennas where circular polarization is desired. However, the limited footprint size of these circularly polarized patch antennas limits their gain [3-5]. Another drawback of the patch antennas is their narrow bandwidth. A few typical existing antenna solutions used in commercial handheld UHF RFID readers are summarized below in Table 1.

Polarization \ Gain	Low (0-3 dBi)	High (3-6 dBi)
Linear	Patch, dipole	Patch, Yagi
Circular	Patch	Patch

TABLE I. TYPICAL ANTENNASOLUTIONS IN HANDHELD RFID READERS

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Fig. 2. Examples of antennas used in commercial handheld UHF RFID readers: a – Tracient [6], b – IPICO [7], c – Unitech [8], d – Skeye [9].

A few typical commercial handheld readers are shown in Figure 2. Tracient reader [6] (Figure 2a) uses low gain linearly polarized antenna, IPICO reader [7] (Figure 2b) uses high gain linearly polarized antenna, Unitech reader [8] (Figure 2c) uses low gain circularly polarized patch antenna, and Skeye reader [9] (Figure 2d) uses high gain circularly polarized antenna. The helical antenna for handheld reader which we describe in this paper is an alternative to large (compared to mobile computer) circularly polarized patch antenna solution shown in Figure 2d.

Helical antennas invented by Kraus [10] have been known and studied for more than 60 years. Besides Kraus, many contributions to helical antennas were made by other researchers [11] and especially by King [12] and Nakano [13] who investigated axial mode antennas. A classical reference on helical antennas is the book by Kraus [14]. Another good modern reference is the book by Balanis [15]. Key parameters of the helical antenna are the diameter D, the turn spacing S, and the number of turns N. Other classical parameters are the circumference $C = \pi D$, the length of the turn $L = \sqrt{C^2 + S^2}$, and the pitch angle $\alpha = tan^{-1}\frac{S}{C}$. The geometrical relationship between these parameters can be illustrated using well known diagram (from [14]) shown in Figure 3.

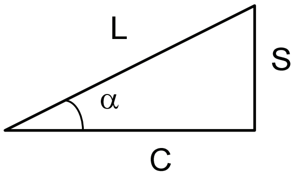


Fig. 3. Geometrical relationship between helical antenna parameters (from [14]).

Helical antennas can operate in several different modes. Figure 4 reproduces a classical chart from [14] which illustrates various modes of helical antennas.

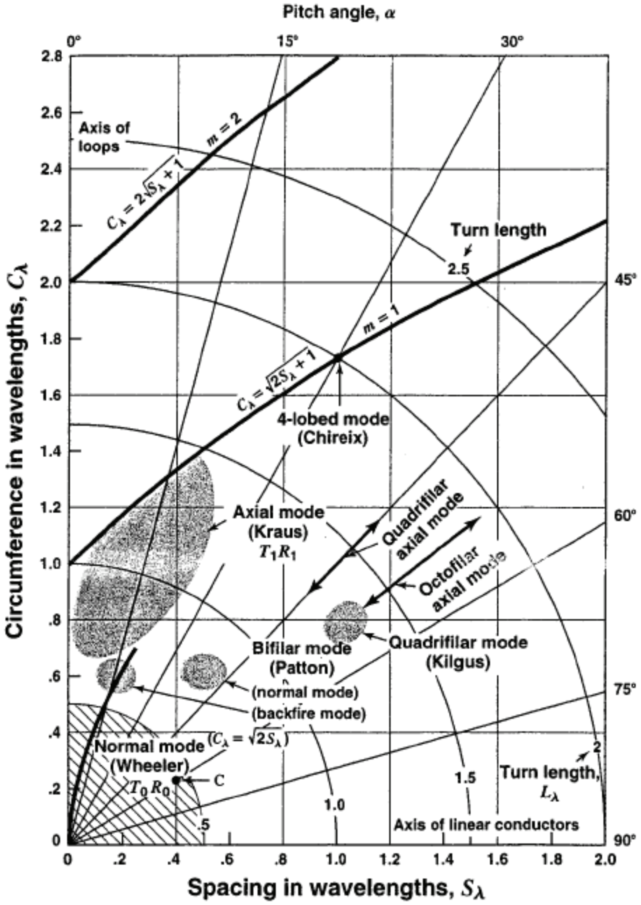


Fig. 4. Helical modes chart (reproduced from [14]).

There exist a number of well known approximate empirical design formulas for helical antennas operating in various modes [12, 14, 15]. For example, the maximum linear gain G, the axial ratio AR, and the half-power beamwidth $HPBW$ of an axial mode monofilar helical antenna in free space can be approximated as [14]:

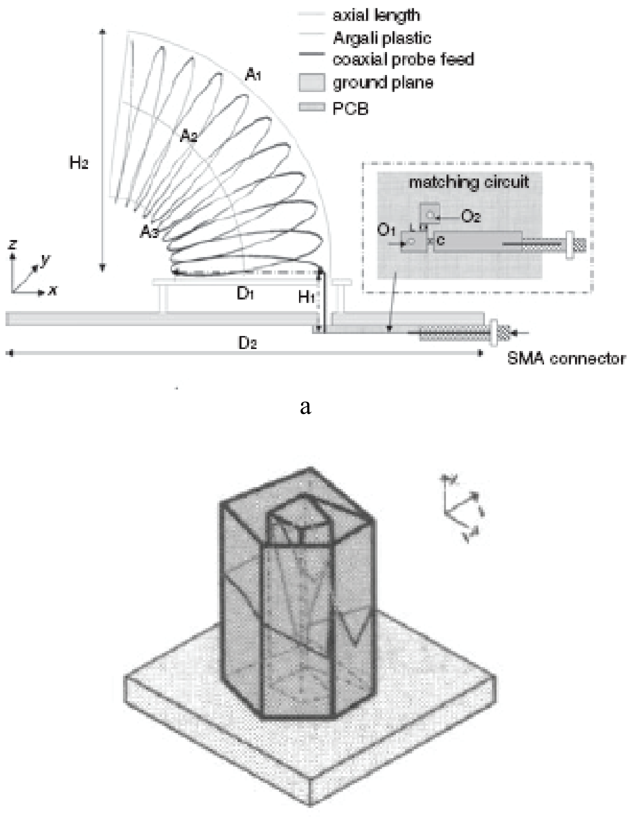
$$G \approx 12N\left(\pi\frac{D}{\lambda}\right)^2 \frac{S}{\lambda} \quad , \tag{3}$$

$$AR \approx \frac{2N+1}{2N} \quad , \tag{4}$$

$$HPBW \approx \frac{52\,deg}{(C/\lambda)\sqrt{N(S/\lambda)}} \quad . \tag{5}$$

When a monofilar helical antenna is operated in axial mode, it can deliver high gain and good circular polarization. However, such antennas usually employ a large number of turns and a large ground plane size (a wavelength or more) which prohibits their use in compact devices such as RFID handheld readers.

In UHF RFID, small low-gain helical antennas have been primarily used in their normal mode (radiating transversal to their axis) for tags [16]. A couple of recent works described the potential use of axial mode helical antennas for readers (accordion shaped helix [17] shown in Figure 5a and polygonal helix [18] shown in Figure 5b) but the size and the construction of those antennas were impractical for handheld readers (for example, accordion shaped helix [17] required a ground plane 12" x 12" and polygonal helix [18] was built with copper tape on a folded cardboard piece).



a

b

Fig. 5. Examples of helical antennas proposed in academic technical literature for handheld UHF RFID readers: a – accordion helix [17], b – polygonal helix [18].

It is known that when the size of the ground plane is reduced, helical antenna starts operating in the backfire mode (maximum gain is in the opposite direction) [19-20]. High gain helical antennas in this regime have been primarily used as satellite feeds [19].

We propose to use the monofilar backfire helix, with some additional modifications [21], as a compact handheld RFID reader antenna. The mode of operation of such helical antenna is backfire axial radiation. The antenna is designed so that it can be integrated into the plastic (hollow core and radome) to ensure mechanical robustness and ruggedness of the whole handheld reader.

II. ANTENNA DESCRIPTION

The proposed antenna is a helix with the ground plane on top and the reflector on the bottom, whose diameters are approximately the same as the diameter of the helix itself. The antenna structure is shown in Figure 6. The antenna is fed via coaxial cable through the opening in the bottom reflector. The cable goes through the center axis of the helix (to minimize the influence on the axial radiation) and connects to the microstrip line implemented on one side of the top PCB whose other side serves as the ground plane. The helix (wire or tape) is connected directly to the microstrip line. The antenna has uniform cross-section along the length and delivers high gain, wide impedance bandwidth, and good circular polarization, as described in details below. The presence of the bottom reflector allows one to increase the antenna gain and to shield the antenna back lobe radiation from the operator hand.

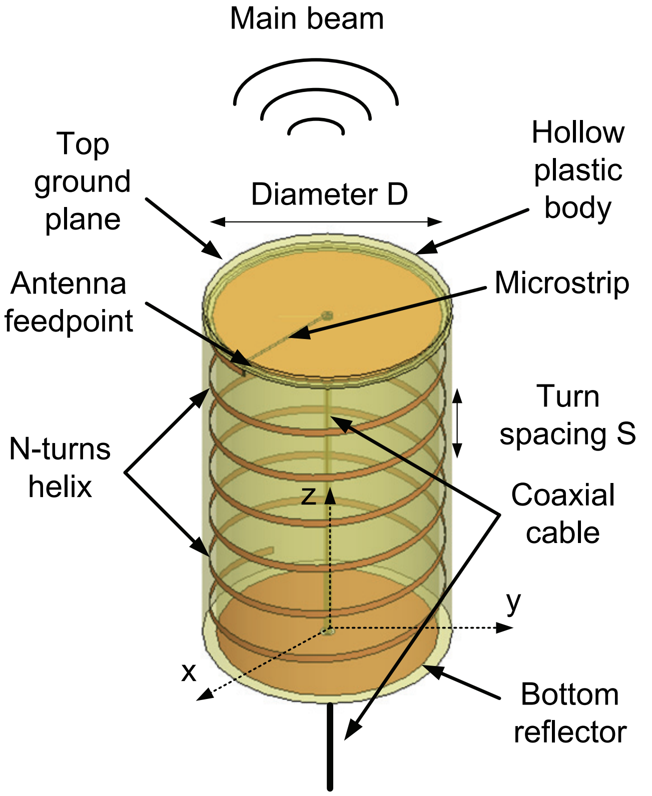


Fig. 6. Proposed antenna structure.

Similar to classical helical antennas, key parameters in the design of the antenna shown in Figure 6 are the diameter *D*, the turn spacing *S*, and the number of turns *N*. Design equations 3, 4, and 5 generally valid for helixes in free space can be used as a good starting point for the design of our helical antenna. However, because this antenna will be used in a rugged handheld device, it will be encased in plastic and hence free space approximations do not really hold. Optimal combinations of *D*, *S*, and *N* for best antenna gain, bandwidth, and axial ratio for particular dielectric material (used for core and radome) have been found from extensive simulation and prototyping.

III. SIMULATION AND MEASUREMENTS

The antenna was modeled and simulated using *Ansoft HFSS* [22]. The main emphasis was on obtaining the desired maximum linear gain in axial direction (6 dBil or better) and an axial ratio of 2 dB or better while conforming to the form factor of a compact cylinder, preferably with diameter less than 3.5 inches and length less than 5.5 inches. Because the antenna was designed to be mounted on a rugged handheld reader for use in harsh environment, an industry standard plastic material (ABS, dielectric permittivity 2.8 with tangent loss 0.001) was chosen for both core and radome. The antenna was optimized to achieve a balance between the size, gain, axial ratio, and impedance bandwidth.

Several versions of the antenna were designed and prototyped. Table 2 below gives parameters of one particular antenna designed to resonate at 895 MHz and to cover 865-925 MHz bandwidth with VSWR < 2, linear gain > 6 dBil, and axial ratio < 2 dB.

Parameter	**Value**	**In free space wavelengths at 895 MHz**
Number of turns N	6	
Height	130 mm	0.39 λ
Diameter D	85 mm	0.25 λ
Circumference C	267 mm	0.80 λ
Turn spacing S	20 mm	0.06 λ
Turn length L	268 mm	0.80 λ
Pitch angle α	4.3 deg	

TABLE II. ANTENNA PARAMETERS (λ =0.335 M @ 895 MHZ)

The simulated radiation pattern this antenna at 895 MHz is shown in Figure 7. Half power beamwidth of this antenna was approximately 70 degrees both in E- and H- planes.

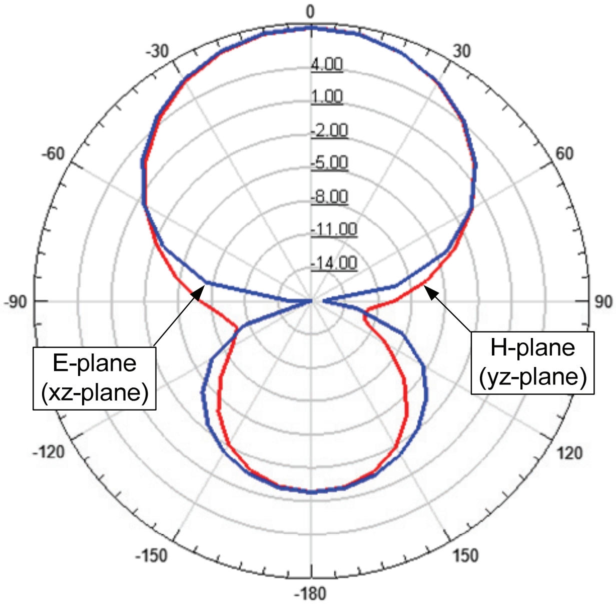


Fig. 7. Simulated 895 MHz radiation pattern of the antenna described in Table 2 (gain is on dB scale).

The relatively long length of the antenna (130 mm) and the large number of helix turns (6) allowed us to achieve the desired gain and satisfy ETSI RFID beamwidth requirements [23]. The antenna fit into the form factor (length < 5.5 in, diameter < 3.5 in) dictated by the marketing and ergonomic requirements to the handheld reader. Note that using high permittivity dielectric could possibly further shrink the size of the antenna but would also make it heavier and more expensive. One of the goals in our antenna project was to use the low cost industry standard plastic.

The prototype of this antenna is shown in Fig. 8 in fully assembled form on a handheld RFID reader with a mobile computer. In spite of the solid heavy visual look, the antenna was hollow (except for the center tube with the coaxial cable) and lightweight. The antenna was wound using 1.5 mm diameter copper wire on the hollow light weight dielectric core cylinder (3 mm thick walls) and covered with a radome (1 mm thick walls), both made from ABS plastic using SLA (stereolithography) process [24]. The top ground plane and the bottom reflector were made using circular shape 30 mil FR-4 PCB (Flame Resistant Printed Circuit Board). The antenna was directly matched to 50 Ohms and fine tuned by adjusting the length of the helix. If desired, an external impedance matching network can also be easily created for this antenna and integrated into the top ground plane, using e.g. tapered microstrip feed [25].

Fig. 8. Prototype of antenna described in Table II, shown attached to the handheld UHF RFID reader with mobile computer.

The return loss, realized gain, and axial ratio of the prototype antenna (boresight) were measured in an anechoic chamber. The measurement results and their comparison with simulation are shown in Fig. 9, 10 and 11 for antenna as is (not attached to the reader). The agreement between simulation and measurements was reasonably good. On our opinion, the deviations were mostly due to the fine details of antenna construction, such as the microstrip-helix feed point, and their simplified modeling in simulations.

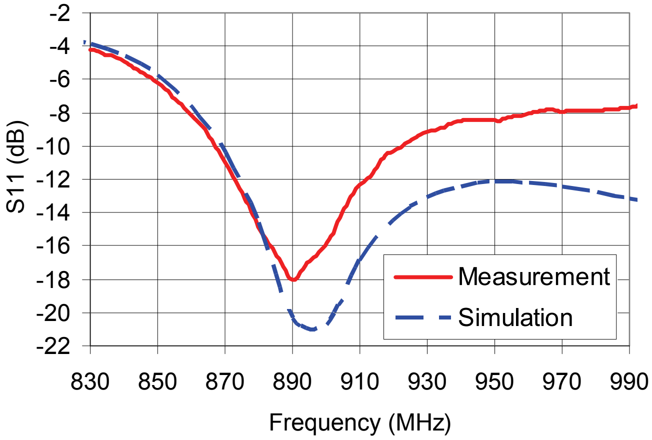


Fig. 9. Measured and simulated return loss of the antenna.

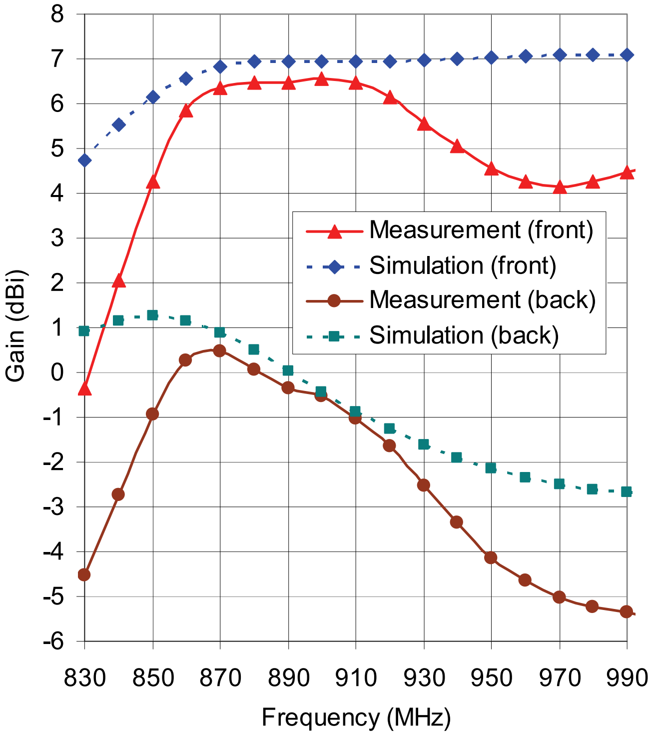


Fig. 10. Measured and simulated boresight linear gain (front and back) of the antenna.

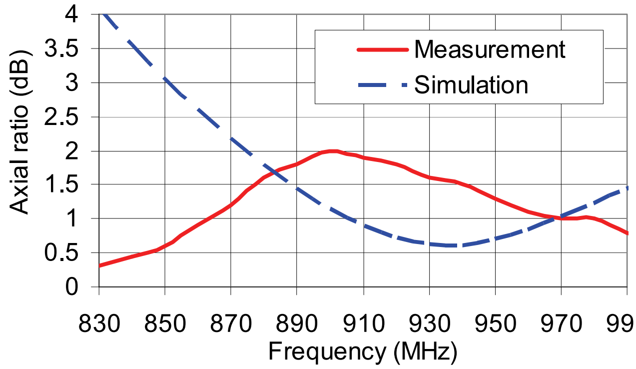
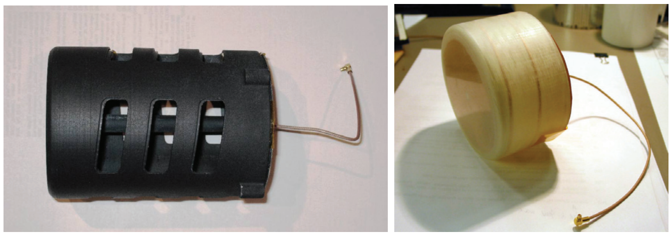


Fig. 11. Measured and simulated axial ratio of the antenna.

One can see that the measured impedance bandwidth (S11<-10 dB or VSWR<2) and gain bandwidth (G>6 dBil) both cover 60 MHz band centered around 895 MHz. This 865-925 MHz band includes ETSI and most of US RFID bands (865-870 MHz and 902-928 MHz). It is interesting to note that for the antenna parameters given in Table 2, empirical formula given by equation 4 predicts axial ratio of 0.34 dB which is within 1-2 dB of both measured and simulated values. However, one should remember that even though the parameters of the antenna in Table 2 are given in free space wavelengths, the antenna is integrated into 4 mm thick plastic (3 mm core wall and 1 mm radome wall). Using free space wavelength value at 895 MHz, equation 3 predicts the gain of 4.4 dBil at 895 MHz, while using the wavelength in dielectric medium with permittivity 2.8 mm results in 11 dBil gain. The true gain values (6-7 dBi) lie between those two estimates.

Other form factors of monofilar backfire helical circularly polarized antennas have also been investigated and several prototypes have been designed, built, and tested. Two of these prototypes are shown in Figure 12. Both were 85 mm in diameter, used the same basic construction as the antenna described above, and were designed for 902-928 MHz band.



a b

Fig. 12. Other investigated antenna form factors.

The antenna shown in Figure 12a was 110 mm long, had approximately 4 turns with 25 mm spacing and had linear gain of 5 dBil. For additional visual appeal, the core and the radome were made in the form of a gun heatshield to show to the potential user that the antenna is hollow and lightweight. The antenna shown in Figure 12b was 50 mm long, had approximately 2 turns with 20 mm spacing and had linear gain of approximately 2.5 dBil. The antenna construction is illustrated in Figure 13 on the example of 110 mm long 5 dBil "gun heatshield" antenna.

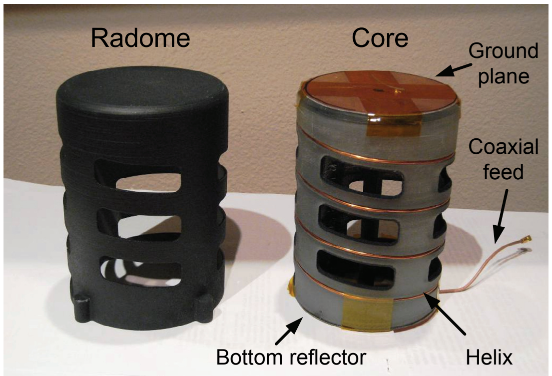


Fig.13. Construction details of "gun heatshield" antenna..

IV. SYSTEM PERFORMANCE

RFID system performance depends on all its components, including readers and tags. The relationship between the tag read range and the reader EIRP shown in Figure 1 was plotted for the case when the system range was limited by the tag sensitivity P_{tag} which defines the forward range. There are other cases when the system range is limited by the reader sensitivity which defines the reverse range. Similarly to equation 2 which defines the forward range, one can define a reverse range in free space as:

$$r_{reverse} = \frac{\lambda}{4\pi}\sqrt{\frac{P_{tag}K}{P_{reader}G_t}}\,, \qquad (6)$$

where K is the tag backscatter loss (which shows how much of the RF power incident on tag is converted to modulated power and backscattered to the reader), P_{reader} is the reader sensitivity, and G_t is the gain of the monostatic reader antenna. Essentially, the reverse range is the maximum range at which the reader can detect the tag response provided that the tag is powered up at the maximum possible distance (given by equation 2).

When performing any RFID system range (read or write) tests or analysis, it is important to understand whether the system range is limited by the tag or by the reader. Relationships given by equation 2 (forward range) and equation 6 (reverse range) are illustrated in Figure 14 as functions of tag sensitivity for 30 dBm monostatic reader with -74 dBm sensitivity and 6 dBi antenna. The tag backscatter loss (which in general depends on the power received by the tag) is assumed for simplicity to be constant at -6 dB.

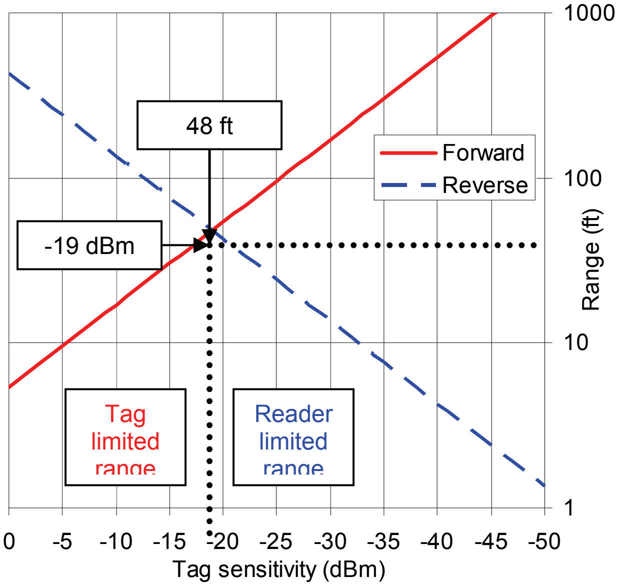


Fig. 14. Free space forward and reverse ranges in RFID system as functions of tag sensitivity for 30 dBm monostatic reader with -74 dBm sensitivity and 6 dBi antenna. Tag backscatter loss is -6 dB.

One can see from the example in Figure 14 that for that particular example, for tags with sensitivity -18 dBm or worse, the free space range is tag-limited for tags with sensitivity -19 dBm or worse but becomes reader limited for tags with better sensitivity. We used that example simply to underline the importance of understanding reader and tag limitations in RFID system tests, especially when reader antennas are being evaluated and compared. One should keep in mind that the reader sensitivity depends on the output power of the reader and transmit-receive leakage which define self-jammer noise, which is much stronger than any outside interference. In general, the stronger is self-jammer, the worse is the sensitivity.

To test the performance of the described helical antenna in real environment and compare it with standard industrial antenna, we used the radio module in our handheld reader operating in ETSI band (869 MHz) under Gen2 (ISO 18000-6C). The reader transmit power was set to 27 dBm. We performed single tag read testing. In warehouse environment, there can be many tags present but the number of tags read per second is primarily defined by how many tags are powered up and what the reader and protocol settings are. The tag which we used for tests was large rigid tag, with sensitivity approximately -13 dBm in 860-960 MHz band [26]. For these selected tag and reader characteristics, our reader had sufficient sensitivity to be sure that the tag read range was forward-limited, and hence directly dependent and indicative of the reader antenna gain.

The antenna to which we compared our helical antenna was was 8 dBic circularly polarized industrial RFID antenna with linear gain approximately 5 dBil at 869 MHz. The antenna was made by Kathrein ([27], model number 52010004) and is shown in Fig. 15. Both antennas were connected one by one to the reader unit and fixed at a height of 0.95 m (typical height of a person's hand above the ground who holds a handheld device). A remote controlled robot carried the styrofoam column with a cardboard piece and RFID tag attached to it and moved along the line away from the reader (as shown in Figure 16), periodically stopping to allow the reader to take measurements of the tag reads. The warehouse floor was re-barred concrete. The tests were done for tags in both horizontal and vertical orientations.

Fig. 15. Circularly polarized RFID antenna by Kathrein [28] used for comparative system testing.

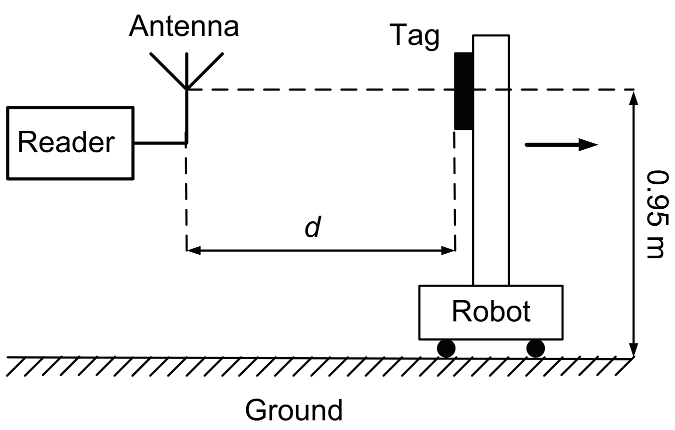


Fig. 16. RFID system testing performed using the same reader module and the antennas shown in Fig. 8 and in Fig. 15.

The results of the tests are given in Fig. 17 and Fig. 18. These tests confirm that in the real RFID warehouse environment our helical antenna showed the axial ratio close to 1.5 dB (the observed ratio between the maximum horizontal and vertical tag ranges in test was about 1.15) and the maximum linear gain of the helical antenna was close to 6 dbil (the maximum range of the tag measured with the helical antenna was about 10% better than with 5 dBil patch antenna).

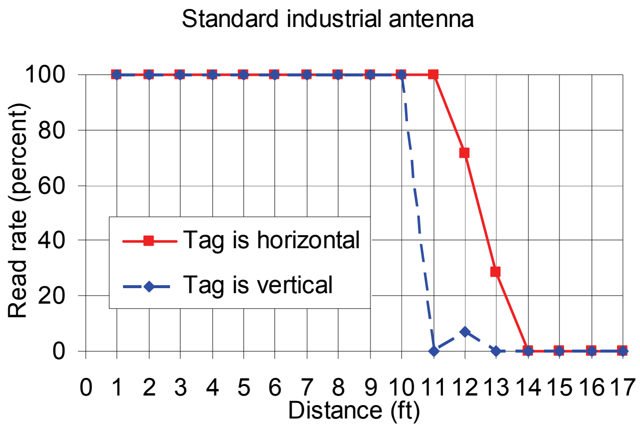


Fig. 17. Tag read rate vs. distance for standard industrial antenna.

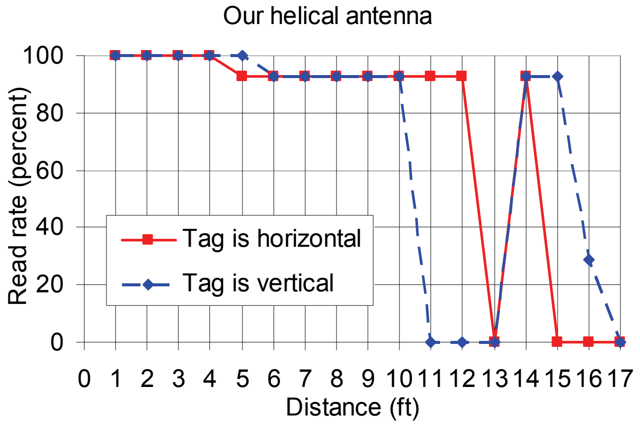


Fig. 18. Tag read rate vs. distance for our helical antenna.

V. CONCLUSIONS

In this paper, we described a compact high gain circularly polarized antenna for use in handheld UHF RFID readers. The antenna was based on a helical structure operating in backfire mode, with additional reflector, had a form factor of compact cylinder 85 mm in diameter, was lightweight and simple in construction (used two PCBs, copper wire for helix, and plastic core and radome). The antenna was modeled, simulated, optimized, prototyped, and measured. The antenna It had maximum linear gain > 6 dBil and axial ratio < 2 dB over 60 MHz band which could be centered to cover any desired portion of the global UHF RFID band (860-960 MHz).

The described antenna is a compact rugged (integrated into plastic) alternative to generic helical antennas built with free-space suspended wires over ground plane and covered with radomes (such as this one [28]) which are not acceptable for handheld RFID reader due to their relatively large size and mechanical instability (to drops, stress, etc.). Due to its compact form factor and performance characteristics comparable to those of large patch antennas used in fixed reader installations, the described antenna can be an attractive solution for handheld readers to maximize tag read range while providing circular polarization and insensitivity to the orientation of tags being read. The antenna was tested and proved its performance in real RFID warehouse environment.

ACKNOWLEDGEMENTS

The authors would like to thank their colleagues Robert Zigler and Sander Lam for help with making antenna prototypes and Rashid Ridwan for help with measurements.

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APPENDIX: LINEAR VS. CIRCULAR GAIN

The linear gain of a circularly polarized antenna (measured in *dBil*) and circular gain of the same antenna (measured in *dBic*) are related as [29]:

$$G\,[dBic] = G\,[dBil] + 20\log\left(\frac{1+10^{-\frac{AR[dB]}{20}}}{\sqrt{2}}\right) \tag{A.1}$$

The difference between the two gains is shown in Fig. 19. When the axial ratio is 0 dB, the difference is 3 dB. In general, depending on the axial ratio, the circular gain of the antenna can be either higher or lower than its linear gain.

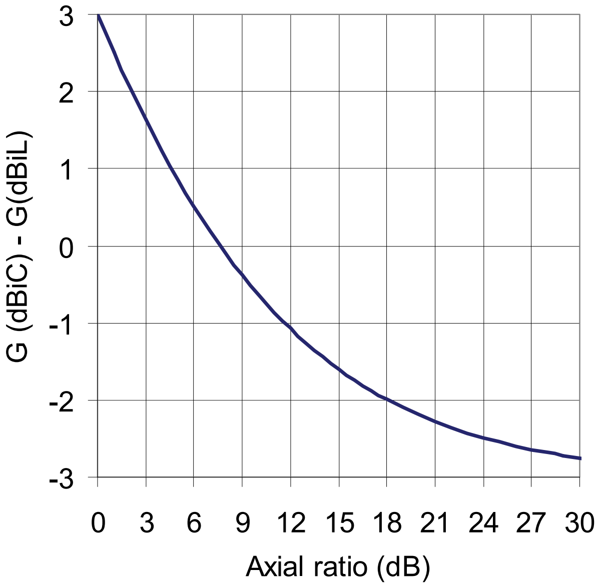

Fig. 19. Difference between circular and linear gains as a function of axial ratio of a circularly polarized antenna.