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Journal of ELECTRICAL ENGINEERING, VOL 67 (2016), NO1, 42–47

ANALYSIS AND DESIGN OF A LONG RANGE PTFE SUBSTRATE UHF RFID TAG FOR CARGO CONTAINER IDENTIFICATION

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In this paper, a high-performances microstrip antenna for UHF (ultra high frequency) RFID (radio frequency identification) tag is designed, prototyped and tested. The antenna consists of two main components: a 1.52 mm RT/duroid 5880 laminate substrate on which the antenna is designed and a 10 mm polytetrafluoroethylene (PTFE) dielectric material placed as a separator between the antenna and the reference ground plane for the microstrip antenna. With this structure, the RFID tag can reach a maximum reading distance of 19 m, although the antenna has a compact size of 80 mm × 50 mm. The long reading distance is obtained by attaching to the antenna an RFID chip that can provide a reading sensitivity of −20.5 dBm. The high bandwidth from 677 MHz to 947 MHz measured at −10 dB, makes the tag being usable worldwide especially for cargo container identification, the main purpose of this research.

K e y w o r d s: UHF tag, microstrip antenna, PTFE substrate, RFID systems, cargo container

1 INTRODUCTION

Nowadays global transportation network is one of the most developed areas and the only way to distribute manufactured products all around the world. This process must be efficient and must assume a high level of security, especially for countries susceptible at terrorist attacks. The US government (and is not the only one) introduced from 2012 a directive which imposes that all the containers coming to the country must have a container security device (CSD) [1]. Usually the transportations are made with cargo containers by roads, water or railways [2]. In this case is important that each container be able to store all the changes in information that occur during transportation, like the last place where was opened and checked. Shipments can be more efficient while the quality of goods transported by the containers is ensured [3].

Identification and authentication of these containers can be made easily with radio-frequency identification technology [4]. Many identification systems for transportation and distribution networks were proposed in the last years, combining RFID technology with GPS (global positioning system), IoT (internet of things) and other systems for an efficient and accurate localization and inventory process [5–9].

A good identification rate of the RFID systems means using tags that can provide high reading distances. The system must provide easy data collection even if the containers are stacked or are deposited in an inaccessible location for human operators. To accomplish this goal, they are needed special tags with a high antenna gain and large beam width that can cover a large identification area and can be mounted on metallic containers.

RFID technology uses a ground communication, so the tag antennas usually have vertical or horizontal polarization, depending on the antenna type. Most of the UHF RFID tags that can be metal mountable and are used for container identification have vertical polarization and use different antenna types.

In [10] a cargo container tag is presented used for tagging metal containers in automotive industry. This type of tag uses a microstrip patch antenna having HDPE (high density polyethylene) as substrate. Although the gain of the antenna is 3.2 dB, the reading distance is 7 m when it is attached to a metallic container. This type of tag is also commercialized and is used in many applications such as automotive containers, metal drums or postal roll cages. Microstrip antennas are also used for making RFID cargo containers tags like the ones presented in [11] and [12]. The first one mentioned has a reading distance of 13 m in free space and 14.7 m attached to a metallic structure. The structure design is simple and can be easily manufactured using a traditional inlay method. Polypropylene with a thickness of 5.08 mm is used as substrate. Another microstrip patched antenna type RFID tag is proposed in [12]. This type has a long read range, more than 20 m, when placed on a metallic sheet. Both tags provide good reading range but they have large sizes. Slot antennas are also used for metallic UHF tags [13]. This type of antenna has a complex design with a small gain (only 2.78 dB) that can provide a long reading distance of 11.5 m. The main disadvantage is given by the bandwidth which is narrowed (approximately 10 MHz). This type of

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DOI: 10.1515/jee-2016-0006, Print (till 2015) ISSN 1335-3632, On-line ISSN 1339-309X

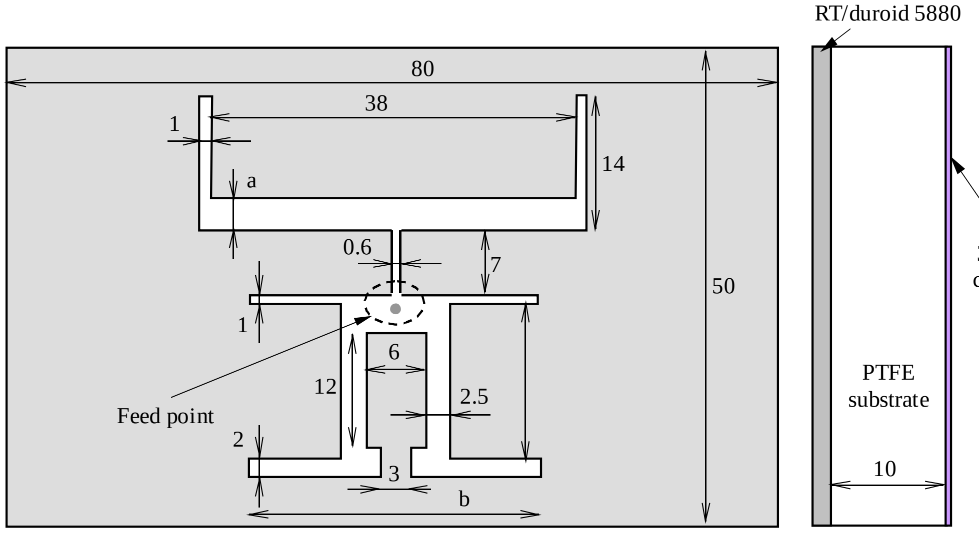

Fig. 1. Configuration of the proposed antenna — geometry and dimensions (mm)

tag can be used only for a specific RFID frequency band, not worldwide. Some other antenna types used for RFID tags are planar inverted-F antennas [14], monopole antennas [15] or cavity structure antennas [16]. Some of these can deliver high gain or large bandwidth, but with the disadvantage of large antenna size. Due to their numerous advantages like the large bandwidth, low fabrication costs and easy for manufacture, microstrip antennas are widely used nowadays for various communication systems [17–20] and are a reference point in this research.

The authors in paper propose a simple design for a microstrip tag antenna used in UHF RFID systems that can provide high gain, large bandwidth and has a reduced size (80 mm × 50 mm × 11.5 mm). For easy manufacturing using a standard photolithography process this antenna does not use any shorting pins. The performance of this design will be compared with some reference RFID tags developed especially for cargo containers or metallic objects identification.

2 ANTENNA STRUCTURE AND DESIGN

Figure 1 shows the geometry and the prototype of the proposed antenna. This antenna has two main parts: a 1.52 mm thickness RT/duroid 5880 laminate ($\varepsilon_r = 2.2$ and $\tan\delta = 0.0009$) on which the antenna is made and a 10 mm thickness polytetrafluoroethylene (PTFE) material ($\varepsilon_r = 2.1$ and $\tan\delta = 0.001$) used as a separator between the antenna and the metallic container.

This type of material helps keeping isolation between the antenna and the metallic structure, reducing the cancelation of the current in the antenna and avoiding the side effects that occur, like decreasing the gain and altering the radiation pattern.

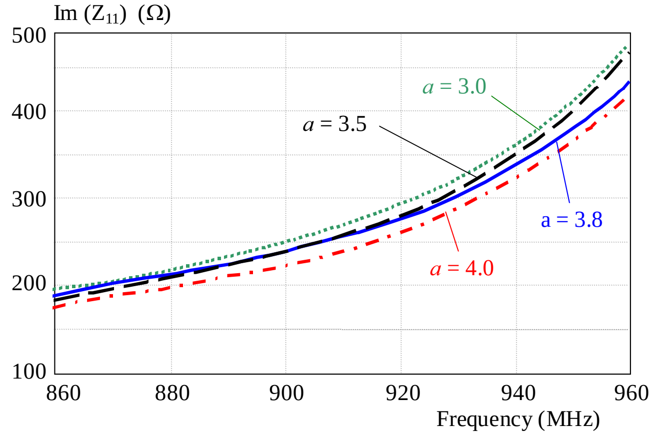

Fig. 2. Variation of the antenna reactance due to variation of the *a* parameter

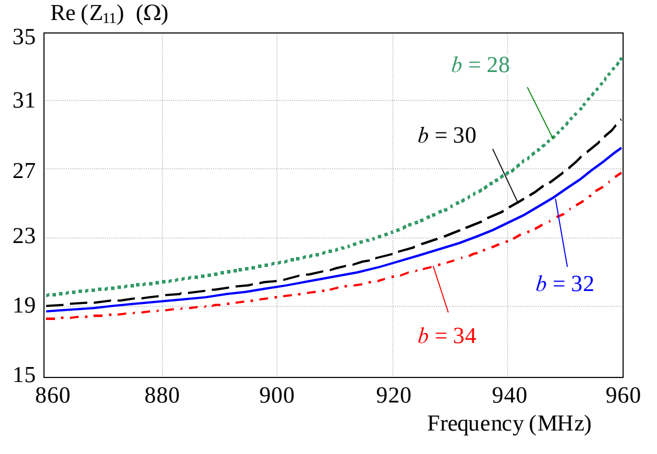

Fig. 3. Variation of the antenna resistance due to the variation of the *b* parameter

As can be seen in Fig. 1, on the bottom of the PTFE material is attached a copper tape as a ground reference for the antenna, which is unavoidable for microstrip antennas and metallic objects application. The design is

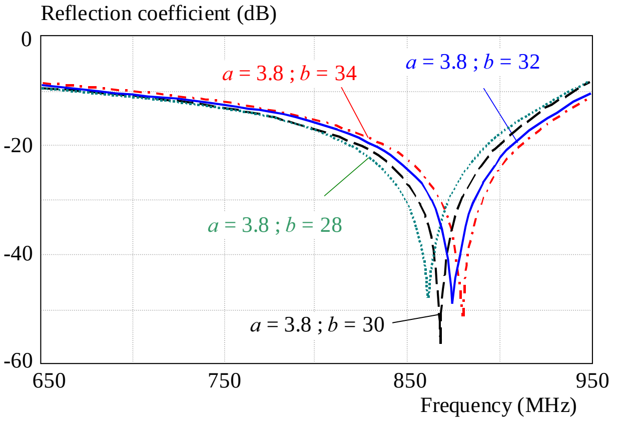

Fig. 4. Variation of the antenna reflection coefficient

Fig. 5. Setup for measuring the antenna impedance

Table 1. Read range results of the proposed tag *vs* other tags

Antennas	Simulated Gain G_τ	Size (mm)	Complexity in prototyping	Reading distance on metal (m)
Proposed	5.94	$80 \times 50 \times 11.52$	No	19
[10]	3.2	$94.5 \times 72 \times 10$	Yes	7
[11]	5.4	$103 \times 97 \times 5.08$	No	14.7
[12]	6.7	$131.25 \times 68 \times 3.17$	Yes	25.4
[13]	2.78	$90 \times 25 \times 3$	No	11.5
[16]	7.1	$240 \times 180 \times 50$	Yes	20.9

chosen randomly, having in the center of the antenna the IC, which is a SOT-323 package type Alien Higgs-4 chip. The gap of 0.6 mm, which is the SOT-323 standard package clearance, is used to facilitate an easy tag chip attachment on the antenna surface. Rests of the values are chosen in a way to optimize the antenna impedance and increase as much as possible the antenna gain.

3 SIMULATED AND EXPERIMENTAL RESULTS

The proposed design is optimized using the electromagnetic (EM) simulator software from ANSYS (Ansoft HFSS 12) and enables an easy control in the antenna impedance $Z_{\text{ant}} = (R_{\text{ant}} + jX_{\text{ant}})$ adjustment. The IC used has an input impedance $Z_{\text{chip}} = (20.5 - j191)\Omega$ obtained at 867 MHz (the central frequency of RFID systems in Europe) and a read sensitivity of -20.5 dBm (the minimum communication power). Below are related some simulations regarding the impedance matching of the antenna with the IC.

The inductive reactance component X_{ant} can be modified by changing the value of the gap from the top-center of the antenna, named a in the Fig. 1. When the width of the gap increases the reactance will decrease and vice-versa. Some simulated values obtained are depicted in Fig. 2. The most effective value for a parameter is 3.8 mm, resulting a reactance value of $192\,\Omega$.

In the same way the resistance component R_{ant} can be modified with the changing of the gaps from the center and the bottom of the antenna (1 mm and 2 mm in width), named b in the Fig. 1. Increasing the gaps length will provide a higher value of the resistance and vice-versa. Both gaps must be changed at the same length in order to ensure the right resistance.

Varying these parameters, the proposed antenna can be easily conjugate-matched to the tag IC impedance $Z_{\text{chip}} = (R_{\text{chip}} + jX_{\text{chip}})$. Like in the previous case, some values obtained by simulation are depicted in Fig. 3.

Another parameter that must be analyzed is the reflection coefficient (S_{11}), which will reveal the resonant frequency of the antenna. Some simulation results regarding this parameter are depicted in Fig. 4. We can see that for $a = 3.8$ mm and $b = 30$ mm, the antenna has a perfect response at 867 MHz, the central frequency of ETSI (European Telecommunications Standards Institute) band. These values where the antenna resonates at 867 MHz will be chosen as the final ones in the tag prototyping process.

After the optimization process using simulations, the tag is prototyped and measured in free space and placed on a metallic sheet of $1000\,\text{mm}^2$ in an EM isolated environment using Agilent FieldFox N9912A Vector Network Analyzer. For measuring the antenna impedance a probe is used made of a $50\,\Omega$ coaxial cable and a semi-rigid end-point (coaxial cable with Teflon dielectric) that is attached to the VNA (Fig. 5). The end-point of the probe (which is the measuring point for the tag antenna) is calibrated to $50\,\Omega$ using a calibration kit to remove any parasitic impedances and losses of the cable. Both calibration and measurements were performed from 860 MHz to 960 MHz, to cover all the RFID frequency bands used worldwide.

The obtained impedance of the tag is depicted in Figs. 6(a) and (b), respectively. The differences between the measured values in free space and on metal are small due to the 10 mm teflon substrate from the tag structure used between the antenna and the metallic plate.

Figure 7 shows the measured value of the reflection coefficient for the antenna, in air and attached to a metallic surface. There is a well matched point around 867 MHz, with a value of -54 dB and -48 dB for the antenna mounted on a metallic sheet and in free space, respectively.

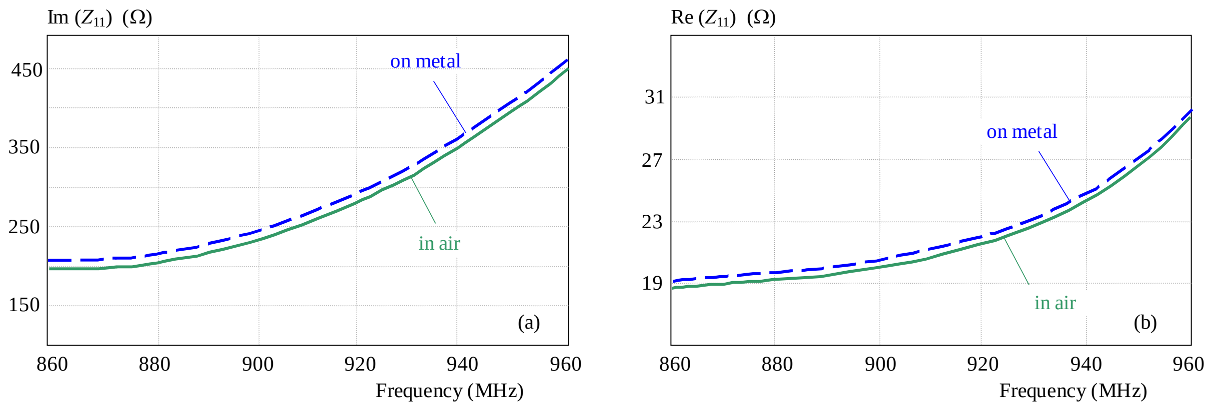

Fig. 6. Measured antenna impedance in air *vs* on metal (a) — Reactance X_{ant}, (b) — Resistance R_{ant}

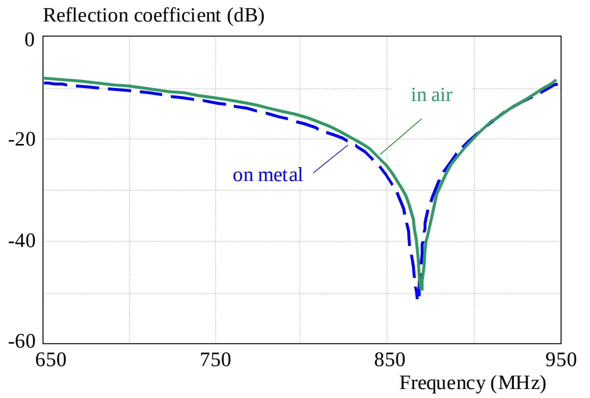

Fig. 7. Measured antenna return loss in air *vs* on metal

The measured -10 dB bandwidth is from 677 MHz to 947 MHz and covers almost all the RFID frequency bands worldwide, exclude Japan, which has a frequency band from 952 MHz to 955 MHz. This antenna bandwidth is wider than a normal microstrip antenna, due to the substrate used as a separator from the antenna and the metallic container on which will be mounted.

The simulated and measured radiation patterns for the ETSI frequency band are depicted in Figs. 8(a) and (b), respectively. The obtained values from simulations and measurements are compared in xz-plane ($\Phi = 0°$) and yz-plane ($\Phi = 90°$), having the Z-axis direction. The maximum peak of the antenna (~ 6 dB) is obtained for 60° beam angle in xz-plane and for 30° beam angle in yz-plane.

In Fig. 9 is a 3D representation of the proposed antenna radiation pattern, which will confirm the peak value mentioned above (~ 6 dB). Due to the metallic surface where is mounted, the antenna has a directive main lobe and a vertical polarization.

The current density on the conductive surface of the antenna is depicted in Fig. 10. Although the distance from the metallic surface is more than 10 mm (if we take into account the thickness of the duroid of 1.52 mm and the thickness of PTFE substrate of 10 mm), we can see that the impedance (Fig. 6) and the reflection coefficient (Fig. 7) have not the same values in free space *vs* on metal due to the parasitic currents that occur on the reference ground plane of the antenna. The PTFE substrate can attenuate more than 95 % of the parasitic current from the reference ground plane and the antenna will maintain approximately always the maximum power transfer with the IC, avoiding power losses and increasing the efficiency of the RFID tag.

4 DISCUSSION

The reading distance of the tag was measured using a commercial ALR-9900+ EMA RFID reader from Alien Technology that can deliver a maximum output power of 33 dBm, having attached a circular polarized antenna with a gain of 5.5 dBiL. The antenna is connected through a cable having a total loss of 0.5 dB. The maximum measured reading distance of the proposed RFID tag is 19 m placed on the 1000 mm^2 metallic sheet and 18.5 m in free space. Achieving a long reading distance (more than 15 m) and maintain the size of the tag small (less than 100 mm) were some starting points regarding this research, which were successfully accomplished. The obtained results are very good and can be compared with other results from some reference designs, which are depicted in Table 1.

Some parameters that were analyzed in the comparison process are the gain of the antenna, size, complexity in prototyping and the reading distance. If we take into account the gain, for the proposed design a value of approximately 6 dB is obtained. This value can be compared with the gain values from [12] and [16]. The size of the tag and the complexity in the prototyping process make the difference between the proposed design in this paper and the designs from [12] and [16]. The values obtained by the proposed model are better than the one depicted in [12] and [16]. If we analyze the complexity of prototyping and the physical dimensions of the tag, some reference designs like those mentioned in [11] and [13] can be compared with the proposed model. These designs cannot provide a long reading range, although the model mentioned in [11] has approximately the same gain as the proposed design.

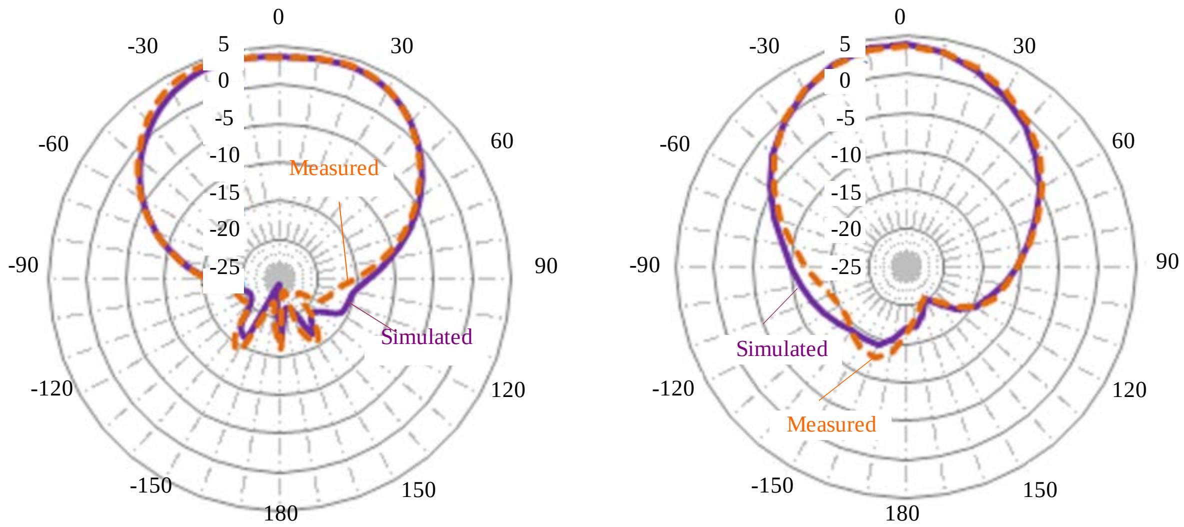

Fig. 8. Radiation pattern of the proposed antenna, (a) — xz-plane ($\Phi = 0°$), (b) — yz-plane ($\Phi = 90°$)

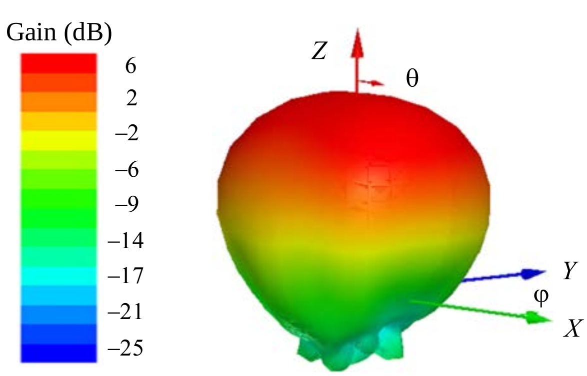

Fig. 9. 3D representation of the antenna radiation pattern

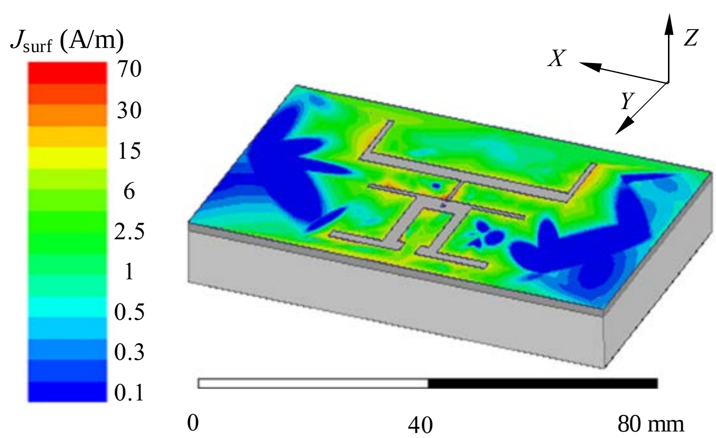

Fig. 10. Current density on the antenna surface

5 CONCLUSION

In this paper a high-performance small sized microstrip antenna used for UHF RFID tags has been designed, prototyped and tested. The proposed tag antenna can be easily tuned with any chip impedance, because of the simplistic design. Using PTFE as a substrate between the antenna and the metallic surface, the gain can reach approximately 6 dB, making the tag being readable up to 19 m. Due to the large bandwidth of the antenna, the UHF RFID tag can be easily used for identification and authentication of the cargo containers worldwide.

This paper was supported by the project "Knowledge provocation and development through doctoral research PRO-DOCT – Contract no. POSDRU/88/1.5/S/52946", project co-funded from European Social Fund through sectoral operational program Human Resources 2007-2013, using the infrastructure from the project Integrated Center for research, development and innovation in Advanced Materials, Nanotechnologies, and Distributed Systems for fabrication and control, Contract No. 671/09.04.2015, Sectoral Operational Program for Increase of the Economic Competitiveness co-funded from the European Regional Development Fund.

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Received 22 September 2015

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