A Resonator Enhanced UHF RFID Antenna Cable for Inventory and Warehouse Applications

Mikko Kokkonen, Sami Myllymäki, Jussi Putaala, and Heli Jantunen

***Abstract*—Structures to improve the RF properties of leaky coaxial cables (LCX) are proposed. These resonator structures are optimized for UHF RFID frequency of 866 MHz; however, they are applicable also to other frequencies of interest by redimensioning with corresponding data. Simulations of leaky coaxial cables with resonators (denoted "RCX") show to improve the antenna gain, which is verified also by measurements. Compared to traditional LCX, RCX have increased radiating power capability while the shape of the propagated wave is also controlled. Cables are simulated with lengths 2.1 m and 6.4 m where the number of radiating slots and resonators is varied. RCXs exhibit a much higher radiation capability than LCXs. The radiation efficiency for RCXs is between 40%···60% whereas an LCX has only 0.2% efficiency. Simulations are complemented with measurements of the 2.1 m cables. A 30x improvement of the read range of passive RFID tags are reported in tests, from 0.05 m to 1.5 m along the resonator cable. The cable length can be extended so that the signal is carried to the radiating point of the cable using conventional, i.e., non-radiating coaxial cable.**

***Index Terms*—Industry 4.0, inventory management, IoT, leaky coaxial cable.**

I. Introduction

LEAKY coaxial cables (LCX) are used as communication cables in subways and mines. It is a coaxial cable type where the outer conductor can have slots of varying geometry and period [1], [2].

LCXs can be divided in two categories: a coupling mode cable where the cable has a continuous slot along the entire length of the outer conductor in the cable and a radiating mode cable where the slots are cut periodically and where the periodicity follows a certain wavelength [3].

Previously, LCXs have been used as communication systems in underground mining and they are evolving towards higher frequency and wider range of applications, such as indoor communication systems and sensors integration [4]–[7], even though an LCX's high frequency limit lies around 6 GHz.

The first use of RFID (radio frequency identification) based system was during WW II in the form of a spy device and identification friend or foe (IFF) transponders. The first research paper was published in 1948 [8]. The study and usage of RFID has grown greatly since then and RFID now covers an even wider range of applications, for example theft protection in stores, inventory management, supply chain management, as attached to pets and it is even used to track people [9]–[16].

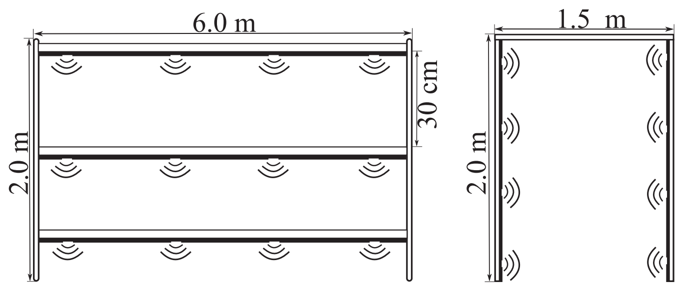

Fig. 1. Presented cable could be installed for ports, gates, and selves in the industry.

Industry is currently implementing UHF RFID systems to digitize production in factories and 17 billion tags are installed yearly in the world. There is an urgent need for radio field control in industrial circumstances.

There have been some improvements made for coupling mode cables. Metal patches have been attached to the cables to enhance coupling loss between the cable and the environment in mobile applications [17], [18].

In this paper we present resonator coaxial cable (RCX) antenna design for UHF RFID applications in 866 MHz. It can be used for example in shelves in warehouses/stores and ports/gates, as in Fig. 1. Several RCX cables can be connected to a multichannel (e.g., 16 channels) RFID reader to increase the reading area or read multiple areas at same time.

There is a need for a spatially controlled radio field to allow the reading of a particular shelf or gate area but not the adjacent shelf or gate area. This is a challenge with current solutions that also read the tags of an adjacent shelf or port. LCXs have short (centimeters) RFID reading ranges along the cable which is a limitation in warehouse applications.

In addition, the radio field in conventional antenna realizations is rather directive and several antenna elements are needed to cover certain spatial areas such as a door or packaging table. LCXs could provide a more sophisticated and economic way to address this with one component.

Passive UHF RFID tags can be read either in near field or in far field. In near field the coupling mechanism for UHF tags can be either magnetic (inductive) or electric (capacitive) but in far field the coupling is capacitive [19].

The space around the LCX/RCX antenna is divided into three different fields: a reactive near field, a radiating near

Manuscript received November 9, 2021; revised December 3, 2021; accepted December 9, 2021. Date of publication December 14, 2021; date of current version December 27, 2021. This research was done in DINO and LAPA projects which were funded by Business Finland. *(Corresponding author: Mikko Kokkonen.)*

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Digital Object Identifier 10.1109/JRFID.2021.3135047

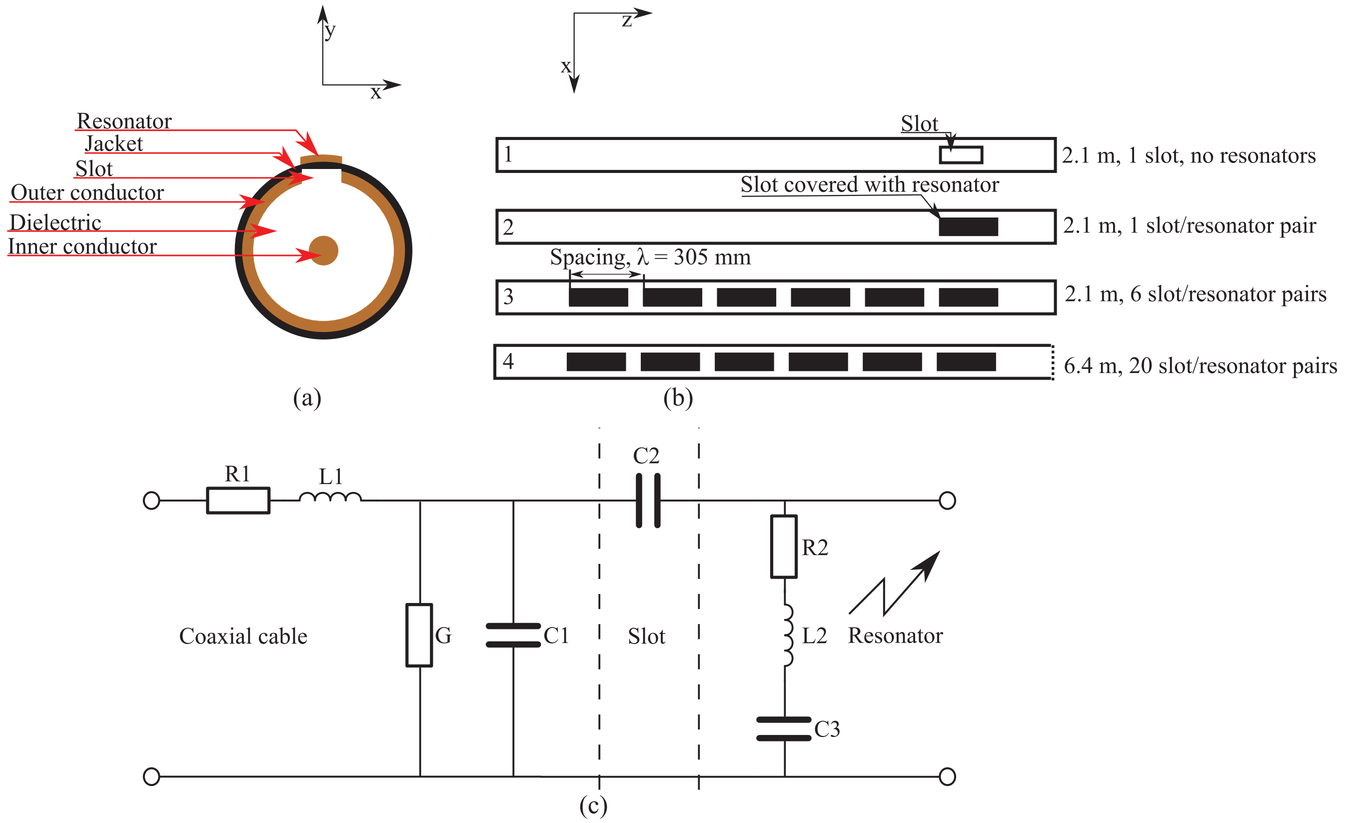

Fig. 2. (a) Cross-section of the leaky coaxial cable and the placement of the resonator on the top of the slot. (b) Schematic of one LCX (Case 1) and three RCXs (Cases 2-4) (schematics are not in any particular scale). Also, coordinate axis is shown. (c) Equivalent circuit of single resonator cable.

field (Fresnel) and a far field (Fraunhofer) [20]. The approximate "boundary" between the fields depends on the ratio between the largest dimension of the antenna and the used wavelength.

The RFID tag reading range is dependent on the electric and magnetic fields and on the tag orientation relative to the fields [21], [22]. In leaky coaxial cables the field's intensity and orientation is controlled by the slot size orientation and the number of slots [23].

RCX design can be used to increase the radiated E- and H-field intensity and to turn the near field radiation into a plane wave without using previously used slot patterns. The radiation pattern control and high intensity are typically needed in 1-30 m use distances in current UHF RFID applications in stores, inventories, and factories.

The presented RCX technology utilizes periodic rectangular slots which are covered by patch type resonators. The resonators are rectangular pieces of metal attached on heat-shrink tubing over the slot.

The resonators' purpose is to couple the energy from the cables to their resonance field and then radiate the energy as the E- and H-fields components and reshape the resultant fields of the RCX resonators. The shape of the resultant fields depends on the number of slots and resonators and their proximity to each other.

Resonating structures have been previously used with RFID microstrip antennas [24]. Also, in the case of a single slot and a resonator (1 m cable length) it has been previously shown how the position of the resonator with respect to the slot affects the S-parameters [25].

This paper presents simulation and measurement results on how RCX performs as an antenna when resonators are used to enhance the leaked electrical field. In Section II working principle of the RCX is discussed and simulation results are reported for S-parameters. Section III presents the measurement results of two fabricated cable antennas showing S-parameters and RFID tag reading range. Section IV concludes the paper.

II. Simulations

A. Working Principle of the RCX and Used Parameters

Fig. 2(a), a resonator coaxial cable consists of an inner conductor, dielectric, outer conductor, and jacket as a typical coaxial cable. The main difference between the typical coaxial cable and resonator cable is that the outer conductor is cut, and the resonator is attached at the top of the slot which increases the field strength of the emitted fields.

Four different cable models were simulated, as presented on Fig. 2(b). Cables 1-3 are 2.135 m (7λ) and 4 is 6.405 m (21λ) long. In the figure, white rectangle describes the slot, while black rectangle describes the resonator on the top of the slot. LCX, i.e., Case 1, has one slot, which was used as a starting point to desing RCX. Other (RCX) cables, i.e., cables 2, 3, and 4, respectively, have one, six, or 20 slots and corresponding number of resonators. Slot (and resonator,

TABLE I
USED SIMULATION PARAMETERS

Parameter	Value
Inner conductor (copper)	⌀4.8 mm
Dielectric (cellular polyethylene)	⌀12.1 mm
Dielectric constant (Dielectric)	1.29
Outer conductor (copper)	⌀13.9 mm
Cable lengths	2.135 m and 6.405 m
Cable impedance	50.0 Ω
Slot	10.0 mm × 40.0 mm
Heat-shrink tubing (polyolefin)	100.0 mm × 50.0 mm
Dielectric constant (Heat-shrink tubing)	2.1
Resonator (copper)	143.9 mm × 7.0 mm
Period (λ)	305.0 mm

where applicable) spacing was fixed to $\lambda = 305$ mm for cables having several slots, i.e., cables 3, and 4. The spacing, i.e., period, was calculated using (1) for 866 MHz according to the permittivity value listed in the cable manufacturer's datasheet [26].

$$\lambda = \frac{c}{f\sqrt{\varepsilon_r}} \tag{1}$$

where c is the speed of light in vacuum, ε_r is the permittivity of the material at the desired frequency, and f is the frequency.

Equivalent circuit of the RCX cable is presented in Fig. 2(c). The equivalent circuit model of the coaxial cable consists of resistance R1, inductance L1, conductance G and capacitance C1.

When a slot is cut to an outer conductor and piece of metal is brought close to it, capacitive connection C2 is formed. Slot size affects the coupling power to the resonator as well as the resonating frequency.

The metal strip acting as a resonator has capacitance C3, inductance L2 and resistance R2. The strip's length and width also affect the resonating frequency by setting the oscillation of the RLC circuit of the resonator, through L2 and C2. Thus, the resonance frequency is a result of many combined effects and factors.

In order to optimize the coupling efficiency, the resonators were installed so that the short edge of the resonator was matched to the short edge (perpendicular to the cable) of the slot. The slot size was initially experimentally evaluated to give good coupling to a metal strip (resonator).

To keep the resonators in place the slot was covered with heat-shrink tubing (polyolefin) and resonators were attached on that. The width of the resonator was 7 mm while the length was optimized by simulations for 866 MHz, being in the UHF RFID frequency band in Europe [27], [28].

Parameter values of the coaxial cable used in simulations are available in the cable manufacturer's datasheet [26] and are appended to Table I which also lists other necessary values for the simulations. CST Microwave Studio was used to simulate the RF behavior of the structure.

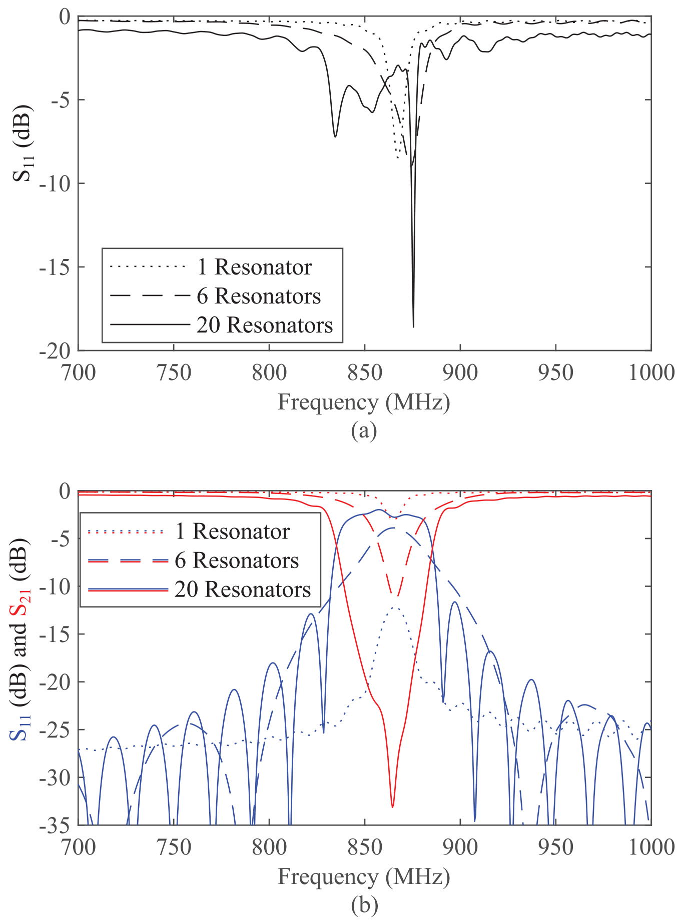

Fig. 3. Simulation results showing S-parameters of RCXs (Cases 2-4) when each cable is (a) open ended (b) terminated to 50 Ω.

B. Simulation Results

Table II shows S-parameter results of the four simulated cable cases. It lists the reflection coefficient S_{11} (in dB) without termination and radiation efficiency, transmission loss, and reflection coefficient when each cable is terminated to 50 Ω.

Starting point cable, LCX, single slotted cable (Case 1) had only 0.2% radiation efficiency. To improve capability of the LCX without changing the slot size, a resonator was attached to the top of the slot as described in the previous section and was optimized for 866 MHz (resonator size is given in Table I).

Simulation results for open ended and terminated RCX (Cases 2-4) are shown in Fig. 3(a) and (b), respectively. Without termination the one- and six-resonator cables show good matching (−8.5 dB, −9.0 dB), at minimum and good radiation efficiency (58%, 54%).

With longer cable and 20 resonators, insertion loss indicated that resonators were tuned to multiple frequencies. This happens because two coupled resonators (or resonant circuits) have two resonant frequencies and having strong coupling between the resonators leads to increased differences between the resonant frequencies [29] which is seen with the 20-resonator cable, Case 4.

Increasing the number of slot-resonator pairs, i.e., the six- and 20-resonator cable (Cases 3 and 4, respectively),

TABLE II
RESULTS FROM SIMULATIONS

Case (Fig.2)	# Slots/resonators	Length (m)	S_{11} at minimun (dB)	Radiation efficiency (%)	S_{21} at minimum (dB)	S_{11} at maximum (dB)
1	1/0	2	-0.1	0.2	-0.2	-23.0
1	1/1	2	-8.5	58.0	-12.1	-12.7
3	6/6	2	-9.0	54.0	-11.4	-3.9
4	20/20	6	-18.0	40.0	-33.1	-2.1

Fig. 4. Photograph of 2.1 m RCX with six slot-resonator pairs. Cable schematic can be found in Fig. 2 (Case 3), slot, and resonators dimensions in Table I.

resulted in increasing insertion loss, but also increasing reflection coefficient, i.e., more power being reflected back to the source.

With one- and six-resonator cable (Cases 2 and 3, respectively) radiation efficiency was 54% which is a considerable improvement over the slotted (LCX) cable, Case 1.

III. Measurements

Two of the simulated RCXs, Case 2 and 3, were prepared following the simulated dimensions (Table I) and characterized in more detail: S_{11} and S_{21} were measured with a Rohde&Schwarz ZVR-B2 vector network analyzer (VNA) in an anechoic chamber. TRL type calibration was used to de-embed measurement setup's cabling from the results. In addition, the RFID tag reading distances alongside the cable were measured by an RFID reader.

RCX preparation included all the steps from cutting the cable to a certain physical length, installing connectors to the ends of the cable, measuring slot locations, cutting the cable jacket and outer conductor, installing heat-shrink tubing and finally installing pieces of metal patch resonators on top of the cable.

One of the fabricated cables (Case 3 in Fig. 2) is presented in Fig. 4. The length of the cable was 2.135 m and number of resonators was six.

A. S-Parameters

S-parameters were measured with a 50 Ohm termination, Figs. 5-6. From Fig. 5 the minimum value of transmission coefficient of the one-resonator RCX is −3.0 dB in simulations and −7.9 dB in measurements.

Correspondingly, in Fig. 6 the transmission loss of the six-resonator RCX is −12 dB (sim.) and −22 dB (meas.).

The best matching of the RCX with one resonator (Fig. 5) was −12.5 (sim.) and −7.9 dB at (meas.), and similarly with

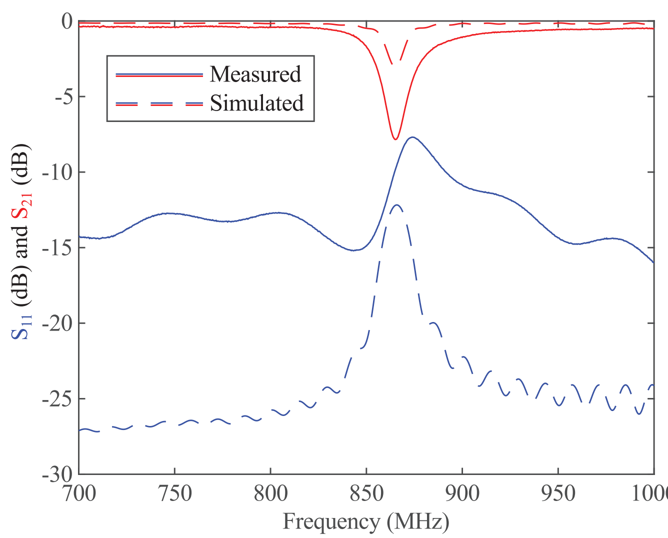

Fig. 5. Measured and simulated transmission coefficient and reflection coefficient in dB of the one-resonator cable terminated to 50 Ω.

the six-resonator case (Fig. 6), −5 dB and (sim. and meas., respectively).

In the single resonator case, there was a 4 dB difference in resonator reflection coefficient and 5 dB difference in insertion coefficient and the frequency was shifted to about 10 MHz higher frequency in the measurements.

The six-resonator case, Fig. 6, had a 10 dB difference in insertion loss between simulations and measurements, while measurements also showed the reflection coefficient peak to exist at approximately 30 MHz lower frequency. It also had a higher overall return loss than the simulated one.

Due the large differences between the simulated and measured S_{11} the single RCX has been simulated and slot size, resonator size, and losses in all materials in present, and even the cable impedance have been changed, i.e., CST was set to

TABLE III
COMPARISON STUDY

Ref	Cable type (LCX or RCX)	Reading range (m)	Input power (dBm | mW)	Cable length (m)	Slotting	RFID tag	Band (MHz)
[22]	LCX	0.1	26 | 400	2.5	Periodic rectancular slots	UH106	865.7
[30]	LCX	0.3 - 0.6	24 | 250	6.12	Periodical triangle slots and one wiggly slot the entire length of the cable	Alien 9662	915
This work	RCX	1.5	30 | 1000	2.135	Periodical rectangular slots covered with a resonator	BELT	866

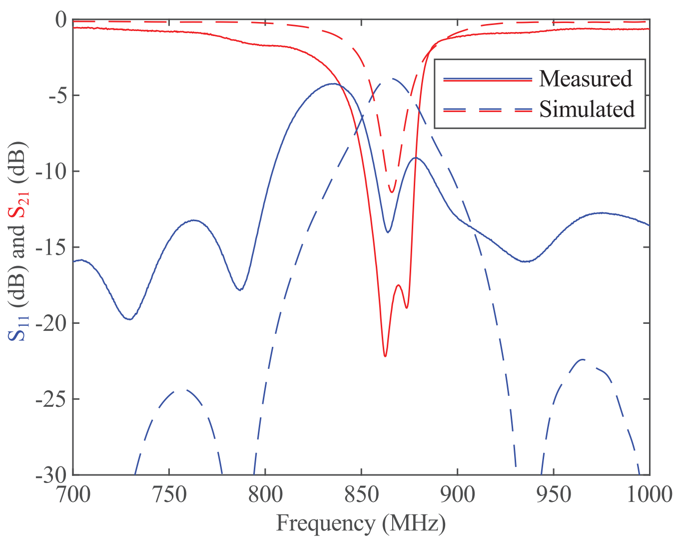

Fig. 6. Measured and simulated transmission coefficient and reflection coefficient in dB of the six-resonator cable terminated to 50 Ω.

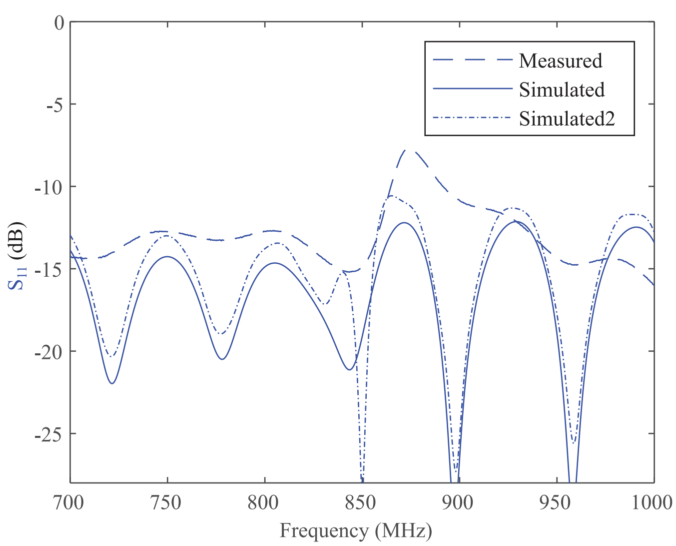

Fig. 7. Comparison of measured S_{11} a single-resonator cable to simulated S_{11} after changing several cable parameters in the simulations (cables were terminated to 50 Ω).

optimize those values in the aim to find the one combination which matches more closely to the measured one, and the result is shown in Fig. 7.

In the optimization, the resonator and slot dimensions as well as the impedance changed the most from the initial values.

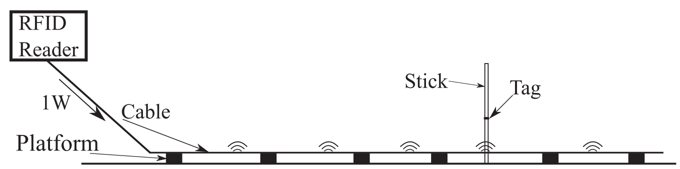

Fig. 8. Schematic of RFID read range test. The stick was moved from end to end of the cable and the tag was raised or lowered according to whether it could be read.

The level of S_{11} is much closer to the measured value, but there are still slight differences that require more detailed and systematic investigation in the future.

In a previous paper, the effect of the resonator displacement, longnitudal, elevational, rotational, and cylindrical, was studied and even a small displacement has an effect on the S-parameters [25].

B. RFID Tag Reading Range Measurement

The capability of the RCX in RFID tag reading was tested and compared to LCX using setup presented in the Fig. 8. The RCX cable was raised 30 cm from the floor by using wooden blocks in order to avoid the floor's reflecting effect. The RFID tag in use was a BELT with NXP UCODE 7 IC made by Smartrac (Avery Dennison) [31]. The reader was a Nordic ID's NUR-05WL2 devkit [32]. A 30 dBm (1000 mW) RF signal was supplied to the cable with the reader.

The tag was attached to a stick (tags' antenna was parallel to the cable) and moved along the cable. The tag was raised or lowered according to whether it could be read, and the maximum was marked up. For a cable with six slots and no resonators the read range was measured to be a few centimeters alongside the cable, while with six-resonator cable reading range improved up to 1.5 ± 0.05 m, which was measured all the way along the cable, which was roughly a fifty times more than the reading range without the resonators.

Comparing to literature, Table III, an LCX with a specific slot pattern had reading ranges of 10 cm [30] or 30 cm to 60 cm [22] depending on the used slotting pattern. It is to be noted that in [30], the input power was smaller, 26 dBm (400 mW), and in [22], 24 dBm (250 mW). Also, the tags were different Alien 9662 (Alien Technology) in [22] and UH106 (LAB ID) in [22].

Due to many differences, it is quite difficult to make a proper comparison between the performance of the RCX and LCX presented in Table III. Nevertheless, the installation of the resonant elements on the LCX clearly improves the RFID reading range.

IV. Conclusion

Leaky coaxial cables with resonators (RCX) exhibit a much higher radiation capability than similarly slotted LCX. The radiation efficiency for RCX was between 40% - 58% whereas an LCX had only 0.2% efficiency. The reading range for a commercial passive RFID tag was improved from 5 cm (LCX) to 1.5 m along the RCX.

The use of resonators in a conventional LCX showed that the leaked electric field strength can be further improved with the resonators, which can be convenient in RFID reading situations where a single long cable antenna is a more suitable solution than connecting multiple individual RFID antennas to the same reader or to multiple readers.

RCX can provide another way to expand reading ranges in UHF-RFID applications such as warehouses and shelves.

In future, RCX with different lengths, different slotting pattern, resonator lengths, and amounts should be investigated to achieve a more optimized structures for different applications.

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