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Emerging MEMS 2010

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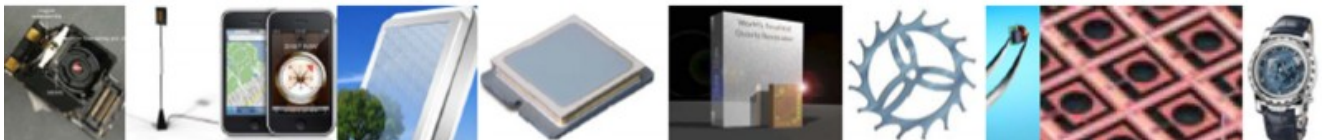
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Design of Novel Paper-based Inkjet Printed Rounded Corner Bowtie Antenna for RFID Applications

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Abstract: This paper presents a novel inkjet printed rounded corner bowtie antenna with T-matching stubs on paper substrate which is the cheapest and widest available substrate. The antenna exhibits compact size with outstanding read range and complete coverage of UHF RFID band (860-960 MHz). The results show extreme immunity of proposed antenna against paper dielectric constant variation. *Copyright © 2010 IFSA.*

Keywords: Bowtie antenna, Inkjet printing, UHF-RFID, Paper substrate, Dielectric variation

1. Introduction

UHF systems generally use far-field coupling, when the antennas of the reader and tag operate in a more conventional way: the forward and reverse link limited read range can be obtained by using Friis equation as [1]. UHF far-field systems typically have greater range than LF and HF systems. Thus they are often used in systems where higher than normal levels of performance are required.

$$R_{forward} = \left(\frac{\lambda}{4\pi} \right) \sqrt{\frac{P_{TX} G_{reader} G_{tag}}{P_{min,tag}}} \quad (1)$$

$$R_{reverse} = \left(\frac{\lambda}{4\pi} \right) \sqrt[4]{\frac{P_{TX} T_b G_{reader}^2 G_{tag}^2}{P_{min,rd}}} \quad (2)$$

where λ is the wavelength, P_{TX} is the reader transmitted power, G_{reader} is the gain of the reader antenna, G_{tag} the gain of the tag antenna, $P_{min,tag}$ is the minimum threshold power required to turn on the tag chip and T_b is the backscatter transmission loss respectively. From equation (1) & (2) it is deduced that the changeable parameter is only the gain of the tag antenna when the reader measurements and tag IC are fixed.

Systems with carrier frequencies above 100 MHz generally operate by transferring power in the far field. The most commonly used frequency bands are in the region of 900 MHz, although the ISM band centered at 2.45 GHz is also used (this band is sometimes termed microwave rather than UHF) [2].

The emerging trend towards low cost, flexible and high performance electronics for automated identification of objects is leading to complex integration techniques. Three major challenges exist in today's RFID technologies. One is the design of small-size tag antennas with very high efficiency and effective impedance matching for IC chips with typically high capacitive reactance. In RFID system it is essential to optimize the antenna for power performance, especially for passive or semi-active configurations, where the only energy source is the incoming reader energy. Another major challenge is the existence of various different UHF frequency bands ranging from 860 to 960 MHz for Europe (866-868 MHz), Asia (864-954 MHz) and US (902-928 MHz). The universal operation of the RFID necessitates the use of wideband antennas covering all three bands. The third obstacle is the realization of ultra-low-cost RFID tags, with a cost requirement for individual tags below one cent [3]. This is only possible by using ultra low cost substrate and small sized antenna structures so that less amount of ink is used for their inkjet printing.

Antenna as shown in Fig. 1 is Inkjet printed on paper substrate of 270 μm thickness using printer from Fujifilm Dimatix, Inc. [4]. In this inkjet process the thickness of printed structures is less than 1-2 μm and significant higher thickness cannot be possible even by printing multiple layers. The fine sized inkjet nozzle cannot work with micrometer sized particle inks used in flexographic and screen printing processes so nano particle based inks from Sun Chemicals and Cabot are used in this printing process, conductivity of the ink-resultant film 12.5×10^6 S/m and $4-25 \times 10^6$ S/m respectively, which are lower than that of bulk silver conductivity.

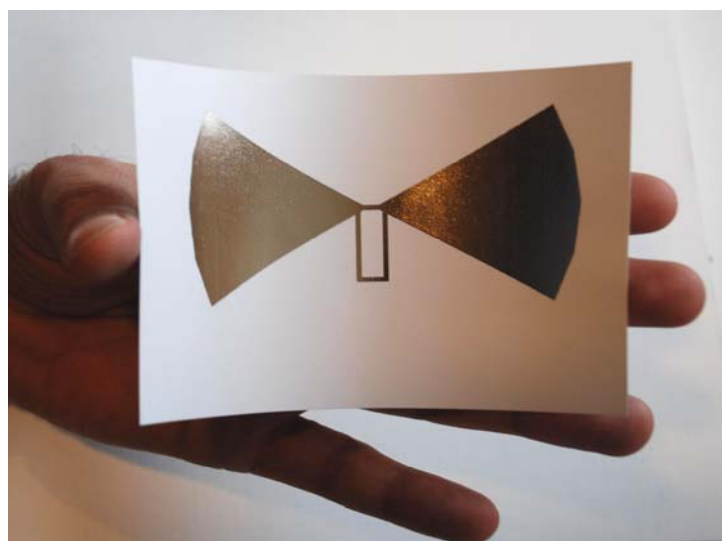


Fig. 1. UHF RFID tag antenna with T-matching stubs.

2. Tag Design Challenges

A key consideration for RFID is the frequency of operation. RFID systems use different bands for communication, the choice of frequency affects several characteristics of any RFID system, the frequency band of interest for presented tag is 860-960 MHz and the choice criteria along with design challenges is discussed below [5].

2.1. Read Range

In the lower frequency bands, the read ranges of passive tags are no more than a couple feet, due to primarily poor antenna gain. (At low frequencies, electromagnetic wavelengths are very high, on the order of several miles sometimes, and much longer than the dimensions of the antennas integrated into RFID tags. Antenna gain is directly proportional to antenna size relative to wavelength. Hence, antenna gain at these frequencies is very low.) At higher frequencies, the read range typically increases. However, because the high frequency bands pose some health concerns to humans, most regulating bodies, such as the FCC, have posed power limits on UHF and microwave systems and this has reduced the read range of these high frequency systems to 10 to 30 feet on average in the case of passive tag which is realized in this project while maintaining the minimum size.

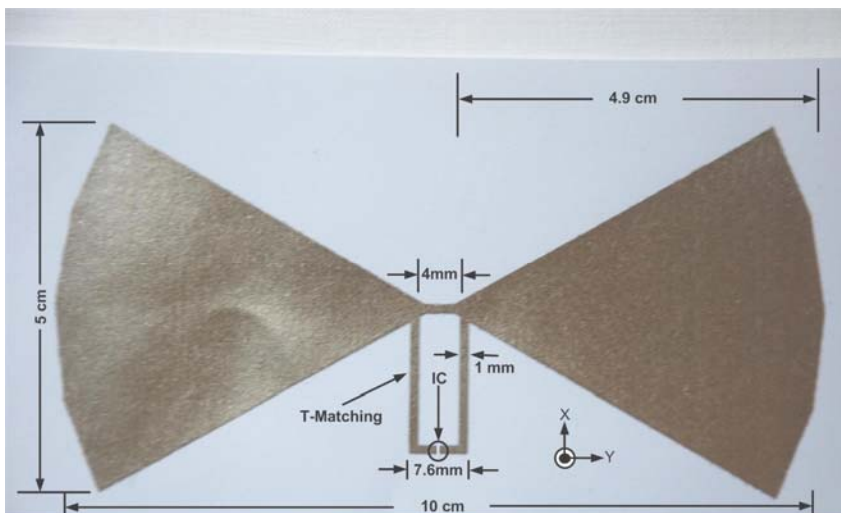


Fig. 2. Printed UHF RFID tag antenna with measurements.

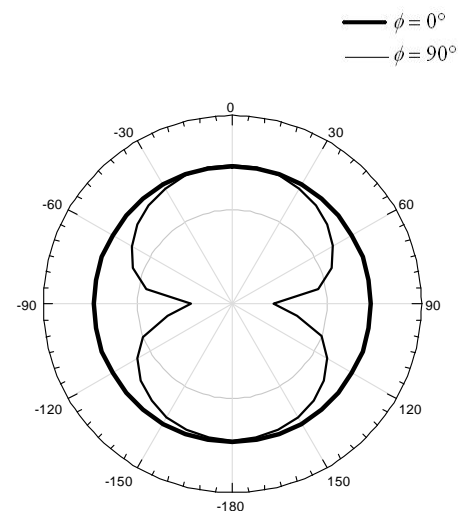


Fig. 3. 2D Radiation pattern.

2.2. Liquids and Metals

The performance of RFID systems will be adversely affected by water or wet surfaces. Signals in the high frequency bands are more likely to be absorbed in liquid. Metal is an electromagnetic reflector and radio signals cannot penetrate it. As a result, metal will not only obstruct communication if placed between a tag and an interrogator, but just the near presence of metal can have adverse effects on the operation of a system; when metal is placed near any antenna the characteristics of that antenna are changed and a deleterious effect called de-tuning can occur. The high frequency bands are affected by metal more so than the lower frequency bands. In order to tag objects made of metal, liquid bearing containers, or materials with high dielectric permittivity, special precautions have to be taken, which ultimately drives up costs. In the presented work the requirement is low cost with integrated capabilities to with stand against these adverse effects to some extent.

2.3. Data Rate

RFID systems operating in the LF band have relatively low data rates, on the order of Kbits/s. Data rates increase with frequency of operation, reaching the Mbit/s range at microwave frequencies [5]. RFID tags in UHF band see the widest use due to their higher data transfer rate (currently 640 kbps for Gen 2 RFID Standard).

2.4. Antenna Size and Type

Due to the long wavelengths of low frequency radio signals, the antennas of LF and HF systems have to be made much larger than UHF and microwave antennas in order to achieve comparable signal gain. This conflicts with the goal of making RFID tags small and cheap. Frequency of operation also dictates the type of antenna used in an RF system. At LF and HF, inductive coupling and inductive antennas are used, which are usually loop-type antennas. At UHF and microwave frequencies, capacitive coupling is used and the antennas are of the dipole type which leads to the selection of proposed rounded corner bowtie antenna (shown in Fig. 2) in our design.

2.5. Size and Price of Tags

Early RFID systems used primarily the LF band, due to the fact that LF tags are the easiest to manufacture. They have many drawbacks, however, such as a large size, as mentioned previously, which translates into a higher price at volume. The HF band is currently the most prevalent worldwide, because HF tags are typically less expensive to produce than LF tags. The UHF band represents the present state of the art. Recent advances in chip technology have brought prices for UHF tags down. The largest barrier to RFID growth is tag cost. Production costs for RFID tags can be broken down as follows

- Silicon die production (1/3)
- Die placement on printed circuit board (1/3)
- Antenna/adhesive packaging (1/3)

This indicates antenna cost plays vital role in production expenses. More complex RFID tags can cost tens of dollars. By the selection of cheapest substrate and printing area reduction by implementing innovative techniques in antenna design, low cost tag is realized here.

2.6. Reliability

RFID tag must be a reliable device that can sustain variations due to temperature, humidity, stress, and survive such processes as label insertion, printing and lamination.

3. Design Process

RFID tag antenna performance strongly depends on the frequency dependent complex impedance presented by the chip. Tag read range must be closely monitored in the design process in order to satisfy design requirements. Since antenna size and frequency of operation impose limitations on maximum attainable gain and bandwidth compromises have to be made to obtain optimum tag performance to satisfy design requirements [6].

RFID tag antenna design process is illustrated on a flow chart shown in Fig. 4. At first the RFID application is selected then system requirements can be translated into tag/antenna design criteria. After these requirements selection of ink for inkjet printing is carried out. The impedance value across the frequency band of interest (860 - 960 MHz) of the selected ASIC (NXP UCODE G2XM) in a chosen RF package (flip chip) to which antenna will be matched can be measured with a network analyzer and verified with datasheet provided by the manufacturer. Antenna parametric study and optimization is performed until design requirements are met in simulation. Like most antennas, RFID tag antennas (derivatives of dipole antenna) tend to be too complicated for analytical solution as they can be used in complex environment. Tag antennas are usually analyzed with electromagnetic modeling and simulation tools, typically with method of moments (MoM) for planar designs (e.g. thin flexible tags) and with finite-element method (FEM) or finite-difference time-domain method (FDTD) for more complicated three-dimensional designs (e.g. thick metal mounted tags). Fast EM analysis tools are crucial for efficient tag design, state of the art CAD tool Ansoft® HFSS is used in this design.

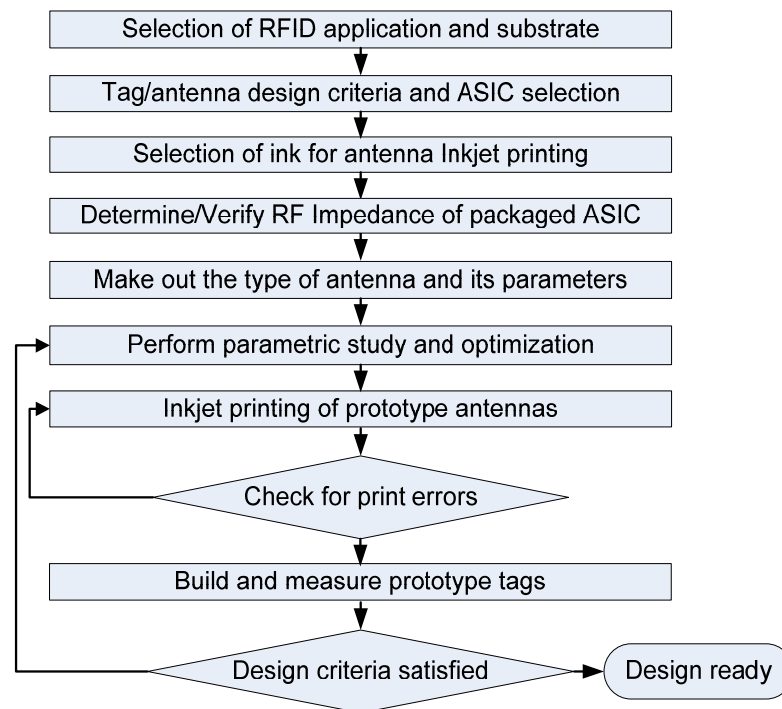


Fig. 4. Inkjet printed RFID tag antenna design process.

In a typical design process, modeling and simulation tools can be benchmarked against measurements. Read range calculation can be implemented directly in EM software by the aid of equations. Tag antenna is first modeled, simulated, and optimized on a computer by monitoring the tag range, antenna gain, return loss and impedance which give to a designer a better understanding of the antenna behavior. In the final two step of the design process, prototype antennas are first Inkjet printed and checked for printing errors and after passing this stage prototype tags are built and their performance is measured extensively. If design requirements are satisfied, the antenna design is ready. If not, the design is further modified and optimized until requirements are met [6].

3. Results and Analysis

The matching with ASIC is achieved by T-matching using stubs as shown in Fig. 2. Good antennas maintain -15 to -20 dB return loss across the entire band of interest [7]. The return loss variation due to

change in paper dielectric constant of proposed antenna is shown in Fig. 5 which shows good agreement with already published results. As required in RFID applications the proposed antenna exhibits a uniform quasi-omnidirectional radiation pattern as shown in Fig. 3 which is mostly the requirement in most of RFID applications. The radiation pattern is in good agreement with the literature [8, 9, 10]. The designed antenna structure is well resistant to variation in paper dielectric constant. Fig. 6 shows the stability of the antenna realized gain against variations, which validates an absolute surpassing performance of this proposed structure cross over the band of interest.

The tag antenna gain is an important parameter for the reading distance. The range is largest in the direction of maximum gain which is fundamentally limited by the size, radiation patterns of the antenna, and the frequency of operation. For a small dipole-like omnidirectional antenna, the gain is about 0-2 dBi [11]. The proposed antenna has demonstrated high gain across the complete UHF RFID band even under critical constrains of size reduction and paper dielectric variations which is in close relation with published results [8, 10]. Fig. 7 shows the simulated impedance variation plots of the antenna, indicating good matching conditions across the frequency band of interest regardless of the variation in paper dielectric constant.

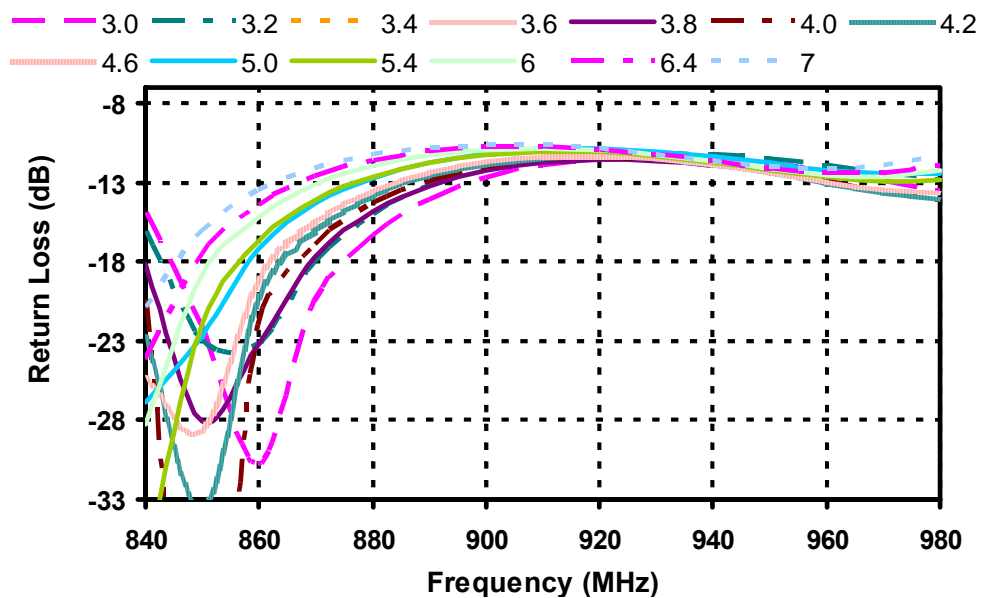


Fig. 5. Return Loss variation (Cabot Ink).

Both lossy and metallic objects may considerably degrade the performance of far-field tag antennas. These objects primarily lower the radiation efficiency of the antenna, and also distort the impedance matching when the tag is placed very close to the objects. In the presented design this effect is also minimized as much possible to a certain extent. The other way is to adopt antennas which have their own ground plane. However, such antennas are usually bulky in size and their multilayer structures are not cost-effective for mass production [11]. The proposed antenna is quite compact in size as well and it occupies only 10 cm x 5 cm. This size is smaller than previously published results [9].

Note that for worldwide operation in the region of 900 MHz, a wide frequency range – approximately 860 to 960 MHz – is required. This means that the antenna must be relatively wideband, with a fractional bandwidth of approximately 11 %. Because of this, the antenna Q is limited, leading to a limited voltage at the tag IC. Importantly, this indicates that there is a trade-off between bandwidth of operation and range [2].

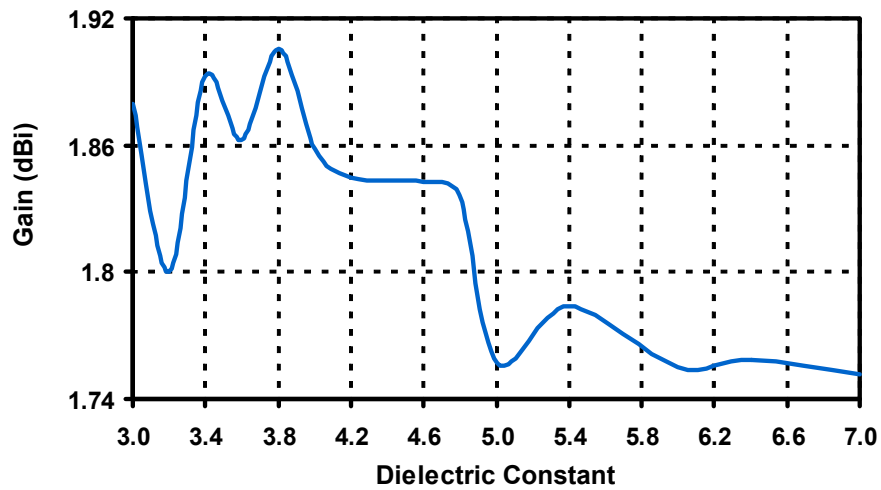
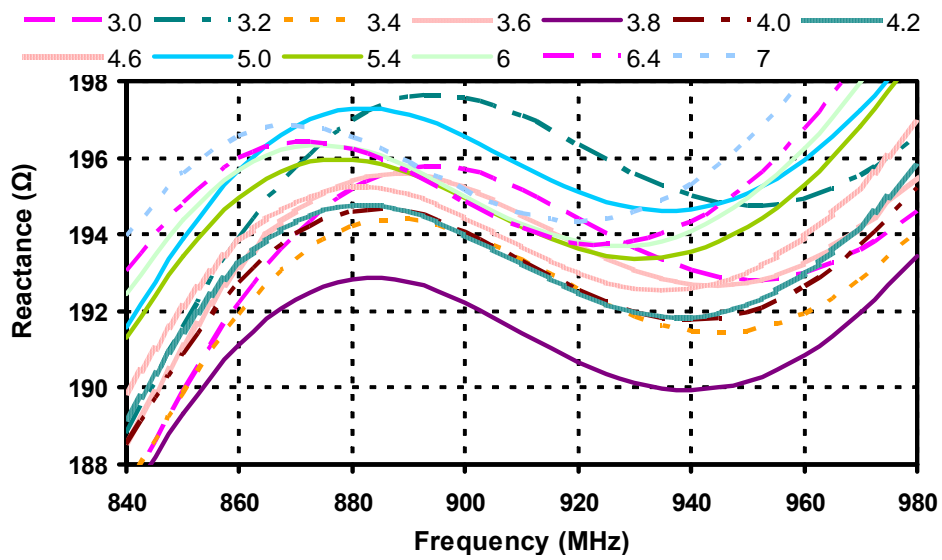
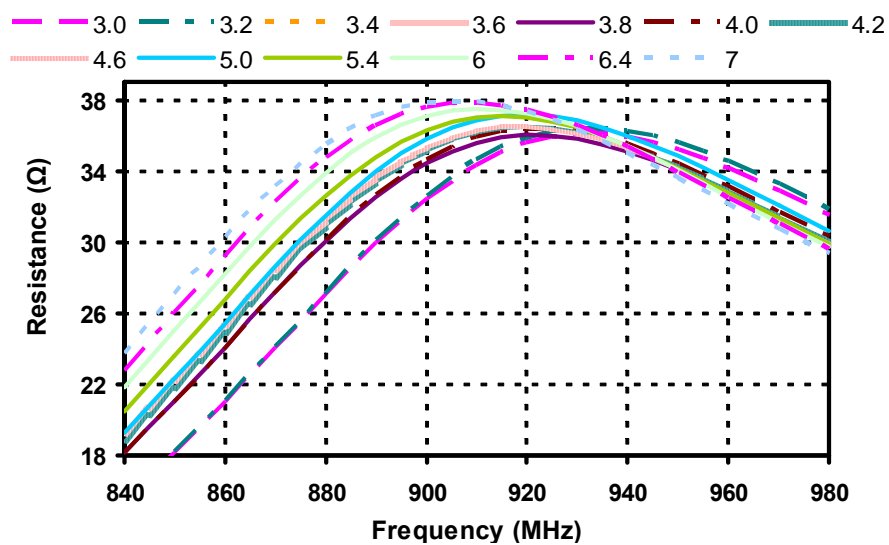


Fig. 6. Antenna Gain Stability (Cabot Ink).



(a)



(b)

Fig. 7. (a) Reactance variation (Cabot Ink); (b) Resistance variation (Cabot Ink).

5. Conclusions

The development of low cost directly printable RFID tag antennas is essential in order to enable item level RFID tracking. The proposed antenna readable across the world due to its coverage of complete UHF RFID band (860–960 MHz) and has significant prospective to be used in small, extremely cheap solutions where read range and/or high data transfer rate is essential. In this paper we have presented extremely versatile antenna with outstanding reading distance of 3.8 meter. We discussed design criteria, challenges outlined generic design process with focus on Inkjet printing and analyzed the results due to variation in paper dielectric constant. The antenna has a wider bandwidth for catering the fabrication disparity. The versatility of this design of the RFID tag is most useful for applications where durability in read range is required, even in the presence of environment which can change the dielectric constant of the substrate. The proposed antenna allows a simple integration directly on e.g. paperboard in a roll-to-roll production line.

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Guide for Contributors

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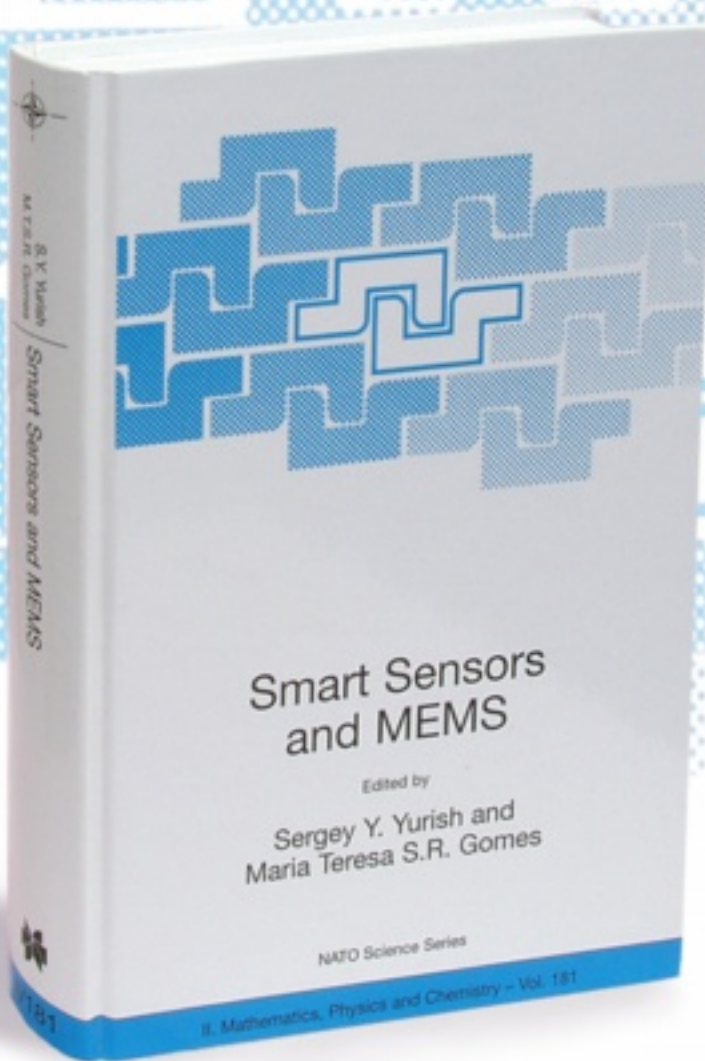
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