Application of metamaterial concepts to sensors and chipless RFID

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Abstract. Several strategies for the implementation of microwave sensors based on the use of metamaterial-inspired resonators are pointed out, and examples of applications, including sensors for dielectric characterization and sensors for the measurement of spatial variables, are provided. It will be also shown that novel microwave encoders for chipless RFID systems with very high data capacity can be implemented. The fields of applications of the devices discussed in this talk include dielectric characterization of solids and liquids, angular velocity sensors for space applications, and near-field chipless RFID systems for secure paper applications, among others.

1. Introduction
In this review paper, it is shown that transmission lines loaded with electrically small metamaterial-inspired resonators can be applied in many diverse scenarios, including sensing of spatial variables, dielectric characterization of solids/liquids, and chipless radiofrequency identification (chipless-RFID). Transmission line metamaterials based on electrically small resonators (particularly split ring resonators –SRRs) were first proposed in [1], where it was shown that, by loading a coplanar waveguide (CPW) with SRRs and shunt inductive strips, left handed wave propagation was possible. On the basis of impedance and dispersion engineering, transmission line metamaterials based on SRRs and other resonant elements (e.g., complementary split ring resonators –CSRRs [2]) have been applied to the design of multiple devices exhibiting improved performance or novel functionalities (filters [3], dual-band components [4,5], enhanced bandwidth components [6], leaky-wave antennas [7], etc.).

In other applications of transmission lines loaded with SRRs or CSRRs (or related metamaterial particles), the resonance phenomenon, rather than dispersion and impedance engineering is exploited [8]. For example, resonator-loaded lines can be applied to the implementation of notch filters. Moreover, as long as the resonance frequency in such lines (transmission zero) is influenced by the region surrounding the resonant element and by the relative position/orientation between the line and the resonator, sensing of material properties [9-34] and spatial variables [35-47] is possible. It is also possible to use chains of resonant elements printed on a dielectric substrate for the implementation of microwave encoders (tags) useful for applications in chipless-RFID. In such RFID systems, tag reading is achieved by means of a dedicated transmission line, through near-field coupling to the tag [48-52].

This paper is focused on reviewing three applications of transmission lines loaded with metamaterial resonators: (i) sensors for angular displacement and velocity measurements, (ii) sensors
for dielectric characterization, and (iii) microwave encoders for chipless RFID. The principle of operation is pointed out for each case, and an illustrative example is provided.

2. Angular displacement and velocity sensors

The type of angular displacement and velocity sensor reported here is based on a transmission line (CPW) loaded with an electrical-LC (ELC) resonator. Such sensors were first reported in [40], and then implemented in microstrip technology in [41], and by using S-shaped SRRs in [44]. The stator is a CPW circularly shaped, whereas the rotor contains a circular ELC resonator axially attached to it (Fig. 1). The ELC of the rotor is placed on top of the CPW in close proximity and parallel to it, so that coupling between the line and the resonator is possible. The working principle is based on coupling modulation by rotation. Namely, the ELC is a bi-symmetric particle, exhibiting an electric wall and a magnetic wall (orthogonally oriented) at the fundamental resonance. If the magnetic wall of the particle is aligned with the line axis (also a magnetic wall), coupling arises, and the transmission coefficient exhibits a notch with significant depth. Conversely, by rotating the particle 90º, i.e., by aligning the electric wall of the ELC with the line axis, coupling is prevented, and the line exhibits total transmission. Obviously, between these two (extreme) situations, the coupling (and hence the notch depth) is modulated by rotation and the relative angle between the line and the ELC can be determined (Fig. 2).

![Fig. 1. Photograph of the stator (a) and rotor (b).](image)

For the measurement of the angular velocity, a harmonic (carrier) signal is injected to the input port of the stator. Through rotor motion, line to resonator coupling is modulated with the result of an amplitude modulated (AM) signal at the output. From the distance between adjacent maxima of the envelope function, the angular velocity can be inferred, provided maximum transmission occurs twice per cycle. The envelope function can be obtained by means of an envelope detector (implemented by a diode and low-pass filter) preceded by an isolator, in order to prevent unwanted reflections from the

![Fig. 2. Transfer function of the notch magnitude at the notch frequency in the transmission coefficient versus the rotation angle. Reprinted with permission from [40].](image)
diode. Figure 3 shows the principle of operation, the experimental set-up is depicted in Fig. 4, whereas Fig. 5 shows the envelope function obtained by an oscilloscope (corresponding to an angular velocity of 3.000 rpm).

![Fig. 3. Schematic of the angular velocity system.](image)

**Fig. 3.** Schematic of the angular velocity system.

![Fig. 4. Photographs of the experimental implementation. Reprinted with permission from [40].](image)

**Fig. 4.** Photographs of the experimental implementation. Reprinted with permission from [40].

![Fig. 5. Measured envelope signal for an angular velocity of 3.000 rpm. Reprinted with permission from [40].](image)

**Fig. 5.** Measured envelope signal for an angular velocity of 3.000 rpm. Reprinted with permission from [40].

3. **Sensors for dielectric characterization**

There are many types of sensors for dielectric characterization based on resonator-loaded lines. Here we report sensors based on frequency splitting [27,29-32]. By symmetrically loading a line with two identical resonators coupled to it, a single notch at the fundamental resonance of the resonant elements arises. However, by truncating symmetry, e.g., by means of an asymmetric dielectric loading, two
notches arise, and the frequency separation between them as well as the difference in the notch depths depends on the level of asymmetry. Therefore, the determination of material properties, specifically the permittivity, of a sample under test (SUT), as compared to a reference sample, can be inferred.

In this paper we report a sensor based on a splitter/combiner configuration [31,32,34], where the splitter/combiner is loaded with a pair of SRRs (Fig. 6) [34]. The sensor is equipped with a pair of microfluidic channels, in order to be able to measure the complex dielectric constant of liquids, particularly, mixtures of deionized (DI) water and ethanol, considering DI water as reference sample (with well known dielectric properties). Fig. 7 depicts the response of the structure for various combination of DI water and ethanol for the SUT, and Fig. 8 shows the variation of the real and imaginary parts of the dielectric constant, inferred from the response of Fig. 7 according to the method detailed in [34].

**Fig. 6.** Topology of the splitter/combiner configuration and relevant dimensions (a) and photograph of the structure including the microfluidic channels for sensing (b). $L = 86$ mm, $W = 62$ mm, inverter dimensions are $l_1 = 27$ mm and $w_1 = 2.22$ mm, SRR dimensions are $l_s = 25$ mm, $W_s = 9$ mm, $c = 1.4$ mm, $g = 2.4$ mm, the slot separation between the lines and the SRRs is $d = 0.2$ mm, and the dimensions of the transmission lines sections between the T-junctions and the SRRs are $l_2 = 9.21$ mm, $w_2 = 1.34$ mm. The ground plane is depicted in grey. Reprinted with permission from [34].

**Fig. 7.** Measured transmission coefficient (magnitude) for different mixtures of DI water and ethanol (LUT), considering DI water as reference liquid. Reprinted with permission from [34].
4. Microwave encoders for chipless RFID

Typically, RFID systems, used for identification and tracking, are based on the use of tags equipped with chips, where the information relative to the object or item is stored. Chipped tags are relatively expensive for many applications involving low-cost items. An alternative to RFID systems based on chipped tags is chipless-RFID [54]. In such systems, the chip is replaced with a planar passive encoder, which contains the identification (ID) code. There are many types of encoders, working in time domain [55-63], frequency domain [48-52,64-80], or even hybrid encoders [77-80], the latter exploiting several domains simultaneously. The main drawback of chipless-RFID systems is the limited data storage capability of the tags (encoders) as well as encoder size. Here we report a chipless-RFID system, where the number of bits is only limited by tag size. The approach, first reported in [51], and subsequently improved in various works [52,81,82], is based on near-field coupling between the reader and the tag and sequential bit reading. The tag is a chain of identical resonant elements etched or printed at equidistant and predefined positions on a dielectric substrate. The presence or absence of resonant elements in such positions determines the ID code. An alternative to tag absence in a certain position is resonator detuning by short-circuiting it, or by any other mean to drastically shift the resonance frequency (i.e., laser ablation, etc.). Tag reading is achieved by means of a transmission line fed with a harmonic signal tuned to the resonance frequency of the tag resonators. In a reading operation, the tag should be displaced above the transmission line of the reader, in close proximity to it, so that the resonant elements sequentially cross the line axis. By this means each time a resonator crosses the line, line-to-resonator coupling prevents the harmonic signal to be transmitted, thus generating an amplitude modulated (AM) signal that contains the ID code of the tag. As compared to other chipless-RFID systems based on multiple resonators, each one tuned to a different frequency (spectral signature barcodes), the proposed tags exhibit much larger data capacity, only limited by tag size. This is due to the fact that the feeding signal is a single tone signal, contrary to the multi-frequency (sweeping) signal required to read spectral signature barcodes, forcing the tag to exhibit a limited bandwidth and hence number of bits.

Figure 9 sketches the proposed chipless-RFID system, whereas Fig. 10 depicts the transmission line of the reader, as well as a 10-bit tag with all resonators (S-SRRs) present at the predefined positions (corresponding to the code ‘1111111111’). It is interesting to mention that the line is loaded with an S-SRR as well (rotated 180° with regard to the S-SRRs of the tag). This is done in order to avoid inter-resonator coupling in the tag as well as coupling between the line and multiple tag resonators, as discussed in [51]. Figure 11 shows the response of various tags with the indicated code, pointing out the validity of the proposed system. This near-field chipless-RFID system with sequential...
bit reading is especially useful in security paper applications, e.g. to avoid unauthorized copies, counterfeiting, etc. of corporate and official documents, ballots, certificates, … Note also that the reported tags have only 10 bits, but this number can be increased at convenience, with the unique limitation of tag size.

Fig. 9. Illustration of the working principle of the proposed chipless RFID system. The cross sectional view is depicted in the inset. The black arrows indicate tag motion in a reading operation. Reprinted from [51] with permission.

Fig. 10. Transmission line reader consisting of the S-SRR-loaded CPW (a) and photograph of the fabricated encoder (b). CPW dimensions are (in mm) \( W = 1.2 \) and \( G = 0.48 \); S-SRR dimensions are (in mm): length \( l_1 = 3.8 \), width \( l_2 = 2.96 \), strip width \( c_0 = 0.4 \) and gap space \( s = 0.2 \). Reprinted from [51] with permission.

Fig. 11. Measured normalized envelope for 3 fabricated encoders with the indicated codes. Reprinted from [51] with permission.
5. Conclusions

In conclusion, it has been shown that transmission lines loaded with metamaterial resonant elements are useful for many diverse purposes, including sensing of material properties, sensing of spatial variables and velocities, and implementation of high data capacity chipless-RFID systems based on near-field coupling.

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References

[1] F. Martín, F. Falcone, J. Bonache, R. Marqués and M. Sorolla, "Split ring resonator based left handed coplanar waveguide", Appl. Phys. Lett., vol. 83, pp. 4652-4654, Dec. 2003.
[2] F. Falcone, T. Lopetegi, J.D. Baena, R. Marqués, F. Martin and M. Sorolla, "Effective negative-stop-band microstrip lines based on complementary split ring resonators", IEEE Microwave and Wireless Components Letters, vol. 14, pp. 280-282, Jun. 2004.
[3] J. Bonache, I. Gil, J. García-García, F. Martín, “Novel Microstrip Band Pass Filters Based on Complementary Split Rings Resonators”, IEEE Transactions on Microwave Theory and Techniques, vol. 54, pp. 265-271, Jan. 2006.
[4] J. Bonache, G. Sisó, M. Gil, A. Iniesta, J. García-Rincón and F. Martín, "Application of composite right/left handed (CRLH) transmission lines based on complementary split ring resonators (CSRRs) to the design of dual band microwave components", IEEE Microwave and Wireless Components Letters, vol. 18, pp. 524-526, August 2008.
[5] M. Durán-Sindreu, A. Vélez, F. Aznar, G. Sisó, J. Bonache and F. Martín, "Application of Open Split Ring Resonators and Open Complementary Split Ring Resonators to the Synthesis of Artificial Transmission Lines and Microwave Passive Components", IEEE Trans. Microwave Theory and Techniques, vol. 57, pp. 3395-3403, Dec. 2009.
[6] G. Sisó, J. Bonache, M. Gil and F. Martín, "Application of resonant-type metamaterial transmission lines to the design of enhanced bandwidth components with compact dimensions", Microwave and Optical Technology Letters, vol. 50, pp. 127-134, January 2008.
[7] G. Zamora, S. Zuffanelli, F. Paredes, F. Javier Herráiz-Martínez, F. Martín, and J. Bonache, “Fundamental mode leaky-wave-antenna (LWA) using slot line and split-ring-resonator (SRR)-based metamaterials”, IEEE Antennas and Wireless Propagation Letters, vol. 12, pp. 1424-1427, 2013.
[8] F. Martín, Artificial Transmission Lines for RF and Microwave Applications, John Wiley, Hoboken, USA, 2015.
[9] M. S. Boybay and O. M. Ramahi, “Material characterization using complementary split-ring resonators,” IEEE Trans. Instrum. Meas., vol. 61, no. 11, pp. 3039−3046, Nov. 2012.
[10] C.-S. Lee and C.-L. Yang, “Complementary split-ring resonators for measuring dielectric constants and loss tangents,” IEEE Microw. Wireless Compon. Lett., vol. 24, no. 8, pp. 563−565, Aug. 2014.
[11] C.-L. Yang, C.-S. Lee, K.-W. Chen, and K.-Z. Chen, “Noncontact measurement of complex permittivity and thickness by using planar resonators,” IEEE Trans. Microw. Theory Techn., vol. 64, no.1, pp. 247−257, Jan. 2016.
[12] M. Puentes, C. Weiß, M. Schüßler, and R. Jakoby, “Sensor array based on split ring resonators for analysis of organic tissues,” in IEEE MIT-S Int. Microw. Symp., Baltimore, MD, USA,
M. Puentes, Planar Metamaterial Based Microwave Sensor Arrays for Biomedical Analysis and Treatment. Springer, Heidelberg, Germany, 2014.

T. Chretiennot, D. Dubuc, and K. Grenier, “A microwave and microfluidic planar resonator for efficient and accurate complex permittivity characterization of aqueous solutions,” IEEE Trans. Microw. Theory Techn., vol. 61, no. 2, pp. 972–978, Feb. 2013.

A. Abduljabar, D. Rowe, A. Porch, and D. Barrow, “Novel microwave microfluidic sensor using a microstrip split-ring resonator,” IEEE Trans. Microw. Theory Techn., vol. 62, no. 3, pp. 679–688, Mar. 2014.

A. Ebrahimi, W. Withayachumnankul, S. Al-Sarawi, D. Abbott, “High-sensitivity metamaterial-inspired sensor for microfluidic dielectric characterization,” IEEE Sensors J., vol. 14, no. 5, pp. 1345–1351, May 2014.

W. Withayachumnankul, K. Jaruwongrungsee, A. Tuantranont, C. Fumeaux, and D. Abbott, “Metamaterial-based microfluidic sensor for dielectric characterization,” Sensor Actuat. A Phys., vol. 189, pp. 233–237, Jan. 2013.

T. Chretiennot, D. Dubuc, and K. Grenier, “Optimized Electromagnetic Interaction Microwave Resonator/Microfluidic Channel for Enhanced Liquid Bio-Sensor,” in Europ. Microw. Conf., pp. 464–467, Dec. 2013.

A. Salim and S. Lim, “Complementary Split-Ring Resonator-Loaded Microfluidic Ethanol Chemical Sensor,” Sensors, vol. 16, pp. 1-13, 2016.

H.-J. Lee and J.-G. Yook, “Biosensing using split-ring resonators at microwave regime,” App. Phys. Lett., vol. 92, no. 25, p. 254103, 2008.

E. Ekmecki and G. Turhan-Sayan, “Multi-functional metamaterial sensor based on a broad-side coupled SRR topology with a multi-layer substrate,” App. Phys. A, vol. 110, no. 1, pp. 189–197, Jan. 2013.

C. Damm, M. Schussler, M. Puentes, H. Maune, M. Maasch, and R. Jakoby, “Artificial transmission lines for high sensitive microwave sensors,” IEEE Sensors Conf., Christchurch, New Zealand, pp. 755–758, Oct. 2009.

C. Damm, Artificial Transmission Line Structures for Tunable Microwave Components and Microsensor Sensors, Shaker Verlag, Aachen, Germany, 2011.

M. Schueler, C. Mandel, M. Puentes, and R. Jakoby, “Metamaterial inspired microwave sensors,” IEEE Microw. Mag., vol. 13, no. 2, pp. 57–68, Mar. 2012.

T. Chen, S. Li, and H. Sun, “Metamaterials application in sensing”, Sensors, vol. 12, pp. 2742-2765, June 2012.

L. Su J. Mata-Contreras, P. Vélez and F. Martin, “Estimation of conductive losses in complementary split ring resonator (CSRR) loading an embedded microstrip line and applications”, IEEE MTT-S Int. Microw. Symp. (IMS’17), Honolulu, Hawaii, June 2017.

L. Su, J. Naqui, J. Mata-Contreras and F. Martin “Modeling metamaterial transmission lines loaded with pairs of coupled split ring resonators”, IEEE Antennas and Wireless Propagation Letters, vol. 14, pp. 68-71, 2015.

J. Naqui, L. Su, J. Mata, F. Martin, “Analysis of transmission lines loaded with pairs of coupled resonant elements and application to sensors”, Journal of Magnetism and Magnetic Materials, vol. 385, pp 144-151, June 2015.

L. Su, J. Naqui, J. Mata-Contreras, F. Martin, “Modeling and applications of metamaterial transmission lines loaded with pairs of coupled complementary split ring resonators (CSRRs)”, IEEE Antennas and Wireless Propagation Letters, vol. 15, pp. 154-157, 2016.

J. Naqui, C. Damm, A. Wiens, R. Jakoby, L. Su, J. Mata-Contreras, and F. Martin, “Transmission Lines Loaded with Pairs of Stepped Impedance Resonators: Modeling and Application to Differential Permittivity Measurements”, IEEE Transactions on Microwave Theory and Techniques, vol. 64, no. 11, pp. 3864-3877, Nov. 2016.

L. Su, J. Mata-Contreras, J. Naqui, and F. Martin, “Splitter/combiner microstrip sections loaded
with pairs of complementary split ring resonators (CSRRs): modeling and optimization for differential sensing applications”, IEEE Transactions on Microwave Theory and Techniques, vol. 64(12), pp. 4362–4370, Dec. 2016.

[32] L. Su, J. Mata-Contreras, and F. Martin, “Configurations of Splitter/Combiner Microstrip Sections Loaded with Stepped Impedance Resonators (SIRs) for Sensing Applications”, Sensors, vol. 16(12), paper 2195, 2016, doi:10.3390/s16122195.

[33] L. Su, J. Mata-Contreras, P. Vélez and F. Martin, “A Review of Sensing Strategies for Microwave Sensors based on Metamaterial-Inspired Resonators: Dielectric Characterization, Displacement and Angular Velocity Measurements for Health Diagnosis, Telecommunication and Space Applications”, International Journal of Antennas and Propagation, vol. 2017, Article ID 5619728, 13 pages, 2017, doi: org/10.1155/2017/5619728.

[34] P. Vélez, L. Su, K. Grenier, J. Mata-Contreras, D. Dubuc, and F. Martin, “Microwave microfluidic sensor based on a microstrip splitter/combiner configuration and split ring resonators (SRR) for dielectric characterization of liquids”, IEEE Sensors Journal, published online.

[35] J. Naqui, M. Durán-Sindreu and F. Martin, “Novel sensors based on the symmetry properties of split ring resonators (SRRs),” Sensors, vol 11, pp. 7545–7553, 2011.

[36] J. Naqui, Symmetry properties in transmission lines loaded with electrically small resonators: circuit modeling and applications, Springer, Heidelberg, Germany, 2016.

[37] J. Naqui, M. Durán-Sindreu, and F. Martin, “Alignment and Position Sensors Based on Split Ring Resonators,” Sensors, vol. 12, pp. 11790–11797, 2012.

[38] A.K. Horestani, C. Fumeaux, S.F. Al-Sarawi, and D. Abbott, “Displacement sensor based on diamond-shaped tapered split ring resonator,” IEEE Sens. J., vol. 13, pp. 1153–1160, 2013.

[39] A.K. Horestani, D. Abbott, and C. Fumeaux, “Rotation sensor based on horn-shaped split ring resonator,” IEEE Sens. J., vol. 13, pp. 3014–3015, 2013.

[40] J. Naqui and F. Martin, “Transmission Lines Loaded with Bisymmetric Resonators and Their Application to Angular Displacement and Velocity Sensors,” IEEE Trans. Microw. Theory Techn., vol. 61, no. 12, pp. 4700–4713, Dec. 2013.

[41] J. Naqui and F. Martin, “Angular displacement and velocity sensors based on electric-LC (ELC) loaded microstrip lines,” IEEE Sensors J., vol. 14, no. 4, pp. 939–940, Apr. 2014.

[42] A.K. Horestani, J. Naqui, D. Abbott, C. Fumeaux, and F. Martin, “Two-dimensional displacement and alignment sensor based on reflection coefficients of open microstrip lines loaded with split ring resonators,” Elec. Lett., vol. 50, pp. 620–622, Apr. 2014.

[43] J. Naqui and F. Martin, “Microwave sensors based on symmetry properties of resonator-loaded transmission lines: a review,” Journal of Sensors, vol. 2015, Article ID 741853, 10 pages, 2015.

[44] J. Naqui, J. Coromina, A. Karami-Horestani, C. Fumeaux, and F. Martin, “Angular displacement and velocity sensors based on coplanar waveguides (CPWs) loaded with S-shaped split ring resonator (S-SRR),” Sensors, vol. 15, pp. 9628–9650, 2015.

[45] J. Naqui, F. Martin, “Application of broadside-coupled split ring resonator (BC-SRR) loaded transmission lines to the design of rotary encoders for space applications”, IEEE MTT-S Int. Microw. Symp. (IMS’16), San Francisco, May 2016.

[46] J. Mata-Contreras, C. Herrojo, and F. Martin, “Application of split ring resonator (SRR) loaded transmission lines to the design of angular displacement and velocity sensors for space applications”, IEEE Trans. Microw. Theory Techn., published online.

[47] A. K. Horestani, J. Naqui, Z. Shaterian, D. Abbott, C. Fumeaux, and F. Martin, “Two-Dimensional Alignment and Displacement Sensor based on Movable Broadside-coupled Split Ring Resonators,” Sensors and Actuators A, vol. 210, pp. 18–24, April 2014.

[48] C. Herrojo, J. Naqui, F. Paredes and F. Martin, “Spectral Signature Barcodes based on S-shaped Split Ring Resonators (S-SRR),” EPJ Applied Metamaterials, vol. 3, pp. 1-6, June 2016.
[49] C. Herrojo, J. Naqui, F. Paredes, F. Martín, “Spectral signature barcodes implemented by multi-state multi-resonator circuits for chipless RFID tags”, IEEE MTT-S International Microwave Symposium (IMS’16), San Francisco, May 2016.

[50] C. Herrojo, F. Paredes, J. Mata-Contreras, S. Zuffanelli and F. Martín, “Multi-state multi-resonator spectral signature barcodes implemented by means of S-shaped Split Ring Resonators (S-SRR)”, IEEE Trans. Microw. Theory Techn., vol. 65, no. 7, pp. 2341-2352, July 2017.

[51] C. Herrojo, J. Mata-Contreras, F. Paredes, F. Martin, “Near-Field chipless RFID encoders with sequential bit reading and high data capacity”, IEEE MTT-S Int. Microw. Symp. (IMS’17), Honolulu, Hawaii, June 2017.

[52] C. Herrojo, J. Mata-Contreras, F. Paredes, F. Martin, “Microwave encoders for chipless RFID and angular velocity sensors based on S-shaped split ring resonators (S-SRRs)”, IEEE Sensors J., vol. 17, no. 15, pp. 4805-4813, August 2017.

[53] O. Weiner, "Die theorie des Mischkorperns fur das Feld der statonare Stromung i. die mittelwertsatze fur kraft, polarisation und energie", Der Abhandlungen der Mathematisch-Physischen Klasse der Konigl. Sachsischen Gesellschaft der Wissenschaften, vol.32, pp.509-604, 1912.

[54] S. Preradovic and N. C. Karmakar, "Chipless RFID: bar code of the future," IEEE Microwave Magazine, vol. 11, pp. 87-97, 2010.

[55] C. S. Hartmann, “A global SAW ID tag with large data capacity,” in Proc. of IEEE Ultrasonics Symposium, October 2002, vol. 1, pp. 65–69.

[56] A. Chamarti and K. Varahramyan, "Transmission delay line based ID generation circuit for RFID applications," IEEE Microw. Wireless Compon. Lett., vol. 16, pp. 588-590, 2006.

[57] M. Schüßler, C. Damm, and R. Jakoby, “Periodically LC loaded lines for RFID backscatter applications,” in Proc. of Metamaterials 2007, Rome, Italy, October 2007, pp. 103-106.

[58] N. Saldanha, D.C. Malocha, “Design Parameters for SAW multi-tone frequency coded reflectors” 2007 IEEE Ultrasonics Symp., pp. 2087-2090, 2007.

[59] M. Schüßler, C. Damm, M. Maasch, and R. Jakoby, “Performance evaluation of left-handed delay lines for RFID backscatter applications,” in Proc. of the IEEE MTT-S International Microwave Symposium 2008, pp. 177-180.

[60] S. Harma, V.P. Plessky, C.S. Hartmann, W. Steichen, “Z-path SAW RFID tag” IEEE Trans. Ultrasonics, Ferroelectric Freq. Control, vol. 55, pp. 208-213, 2008.

[61] H. Tao, W. Weibiao, W. Haodong, S. Yongan, “Reflection and scattering characteristics of reflectors in SAW tags”, IEEE Trans. Ultrasonics, Ferroelectric Freq. Control, vol. 55, pp. 1387-1390, 2008.

[62] S. Harma, V.P. Plessky, L. Xianyi, P. Hartogh, “Feasibility of ultra-wideband SAW RFID tags meeting FCC rules” IEEE Trans. Ultrasonics, Ferroelectric Freq. Control, vol. 56, pp. 812-820, 2012.

[63] F.J. Herraez-Martinez, F. Paredes, G. Zamora, F. Martin, and J. Bonache, “Printed magnetoinductive-wave (MIW) delay lines for chipless RFID applications”, IEEE Trans. Ant. Propag., vol. 60, pp. 5075-5082, Nov. 2012.

[64] S. Preradovic, I. Balbin, N. C. Karmakar, and G. F. Swiegers, "Multi-resonator-based chipless RFID system for low-cost item tracking," IEEE Trans. Microw. Theory Techn., vol. 57, pp. 1411-1419, 2009.

[65] S. Preradovic and N. C. Karmakar, "Design of chipless RFID tag for operation on flexible laminates," IEEE Anten. Wireless Propag. Lett., vol. 9, pp. 207-210, 2010.

[66] O. Rance, R. Siragusua, P. Lemaître-Augier, E. Perret, "Toward RCS magnitude level coding for chipless RFID," IEEE Trans. Microw. Theory Techn., vol. 64, pp. 2315-2325, Jul. 2016.

[67] J. McVay, A. Hoorfar, and N. Engheta, “Space-filling curve RFID tags,” in Proc. of 2006 IEEE Radio Wireless Symp., pp. 199–202.

[68] I. Jalaly and D. Robertson, “Capacitively-tuned split microstrip resonators for RFID barcodes,”
in Proc. of European Microwave Conference, October 2005, vol. 2, pp. 4–7.

[69] H.-S. Jang, W.-G. Lim, K.-S. Oh, S.-M. Moon, and J.-W. Yu, “Design of low-cost chipless system using printable chipless tag with electromagnetic code”, IEEE Microw. Wireless Compon. Lett., vol. 20, pp. 640-642, 2010.

[70] A. Vena, E. Perret, and S. Tedjini, “A fully printable chipless RFID tag with detuning correction technique”, IEEE Microw. Wireless Compon. Lett., vol. 22(4), pp. 209-211, 2012.

[71] A. Vena, E. Perret, and S. Tedjini, “Design of compact and auto-compensated single-layer chipless RFID tag”, IEEE Trans. Microw. Theory Techn., vol. 60(9), pp. 2913-2924, Sept. 2012.

[72] A. Vena, E. Perret, and S. Tedjini, “High-capacity chipless RFID tag insensitive to the polarization”, IEEE Trans. Ant. Propag., vol. 60(10), pp. 4509-4515, Oct. 2012.

[73] M. M. Khan, F. A. Tahir, M. F. Farooqui, A. Shamim, H. M. Cheema, "3.56-bits/cm² compact inkjet printed and application specific chipless RFID tag," IEEE Ant. Wireless Propag. Lett., vol. 15, pp. 1109-1112, 2016.

[74] M. A. Islam and N. C. Karmakar, "A novel compact printable dual-polarized chipless RFID system," IEEE Trans. Microw. Theory Techn., vol. 60, pp. 2142-2151, Jul. 2012.

[75] R. Rezaiesarlak and M. Manteghi, "Complex-natural-resonance-based design of chipless RFID tag for high-density data," IEEE Trans. Ant. Propag., vol. 62, pp. 898-904, Feb. 2014.

[76] M. Svanda, J. Machac, M. Polivka, J. Havlicek., "A comparison of two ways to reducing the mutual coupling of chipless RFID tag scatterers," in Proc. of 21st International Conference on Microwave, Radar and Wireless Communications (MIKON), May 2016, pp. 1-4.

[77] A. Vena, E. Perret, S. Tedjini, "Chipless RFID tag using hybrid coding technique," IEEE Trans. Microw. Theory Techn., vol. 59, pp. 3356-3364, Dec. 2011.

[78] A. Vena, E. Perret, S. Tedjini, “A compact chipless RFID tag using polarization diversity for encoding and sensing”, 2012 IEEE Int. Conf. RFID, pp. 191-197, 2012.

[79] I. Balbin, N.C. Karmakar, “Phase-encoded chipless RFID transponder for large scale low cost applications”, IEEE Microw. Wireless. Comp. Lett., vol. 19, pp. 509-511, 2009.

[80] S. Genovesi, F. Costa, A. Monorchio and G. Manara, “Chipless RFID tag exploiting multifrequency delta-phase quantization encoding”, IEEE Ant. Wireless, Propag. Lett., vol. 15, pp. 738-741, 2015.

[81] C. Herrojo, J. Mata-Contreras, F. Paredes, Ferran Martín, “Near-field chipless RFID system with high data capacity for security and authentication applications”, IEEE Transactions on Microwave Theory and Techniques, submitted.

[82] C. Herrojo, J. Mata-Contreras, F. Paredes, A. Nuñez, E. Ramón, F. Martín, “Near-field chipless-RFID tags with sequential bit reading implemented in plastic substrates”, Journal of Magnetism and Magnetic Materials, to be published.