RF and THz Identification Using a New Generation of Chipless RFID Tags

Etienne PERRET[1], *Maher HAMDI*[2], *Arnaud VENA*[1], *Frederic GARET*[2], *Maxime BERNIER*[3], *Lionel DUVILLARET*[4], *Smail TEDJINI*[1]

[1] Grenoble-INP/LCIS, 50, rue de Laffemas, BP 54, 26902 Valence, France
[2] Grenoble-INP/IMEP-LAHC, Université de Savoie, 73376 Le Bourget du Lac, France
[3] Département de physique, Université de Sherbrooke, Sherbrooke, Qc, Canada J1K 2R1
[4] KAPTEOS, Savoie Technolac, 73376 Le Bourget du Lac cedex

etienne.perret@lcis.grenoble-inp.f, maher.hamdi@univ-savoie.fr, arnaud.vena@lcis.grenoble-inp.fr, frederic.garet@univ-savoie.fr, maxime.bernier3@usherbrooke.ca, ld.kapteos@orange.fr, smail.tedjini@lcis.grenoble-inp.fr

Abstract. *This article presents two chipless RFID approaches where data are reading using electromagnetic waves and where the medium encoding the data is completely passive. The former approach rests on the use of RF waves. The tags are comparable with very specific, planar, conductive, radar targets where the relation between the tag geometry and its electromagnetic signature is perfectly known and is used to encode the data. The data storage capacity of the RF chipless tags is proportional to of the used frequency bandwidth. As radio spectrum is regulated, the number of possible encoding bits is thus strongly limited with this technology. This is the reason why we introduce a new family of tags radically different from the preceding one, where data is encoded in volume thanks to a multilayer structure operating in the THz domain. These two approaches although different are complementary and allow to increase significantly the data storage capacity of the chipless tags. Simulation and experimental results are reported in this paper for both configurations. We demonstrate a coding capacity of 3.3 bit/cm^2 for RFID chipless tags and a potential 10 bits coding capacity in the THz domain.*

Keywords

Chipless RFID, THz identification, electromagnetic response, Photonic Band Gap.

1. Introduction

Electronic tracking of products is a widely growing field. The most familiar tracking techniques are conventional optical barcodes [1], [2]. They are employed to perform various identification purposes. The barcodes are widespread due to their very low cost and ease of fabrication. Barcodes are limited, however, by their short range of reading. In addition to range limitations, barcodes are impossible to read if there is any obstruction between the reading device and the barcode. When reading a barcode, the orientation of the reading device relative to the barcode also appears as a problem. If the reading device is not properly aligned or is held at an improper angle, the encoded information cannot be read. As a result an individual reading operation is required by a human operator.

The magnetic strips are also a very familiar tracking technique which is widely employed in business to perform several identification purposes. In term of using, the magnetic strips are closed to Smart Cards. Indeed, a contact based Smart Card, or magnetic strip requires the insertion of the card into a contact reader. In the specific case of magnetic strips reader, the mechanical part is very important. This leads to a dramatic increase of the reader production and maintenance costs. It is why the global cost of this identification technique remains high. Contrary to barcode, the attractive feature of magnetic strips is that they are writable and rewritable. However, their inherent limitations – costs and not contactless – have prevented their use in a wide range of applications for machine-readable data storage.

The above hurdles may be overcome by reading another technology based on radio waves. RFID is an automatic technique of capturing information coming from a label containing the data by remote radio reading. The label consists of a microchip and an antenna which ensures the communication with a dedicated reader. Recently, this technology has gained tremendous popularity as a device for storing and transmitting information. It has now become inevitable for item identification and tracking applications. Most RFID tags present a longer reliable range than barcodes. Even though rapid growth is predicted by many exploratory studies, its progress is slowed down due to several economical, technological and social factors like the high cost of the tags, the lack of safety and reliability of the information contained within RFID chip, and difficulties in recycling tags. Because applications using RFID present various constraints, each tag design is dedicated for a specific application. And it can be found many variant of RFID depending on several parameters.

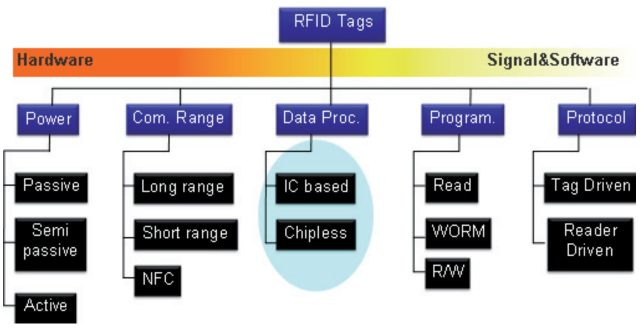


Fig. 1. Classification of RFID tags.

As shown in Fig. 1, the most significant parameters that best describe a RFID tag are the way of empowering, the reading range, the data processing, the read/write capability and the protocol used. In this classification, emphasis is made on the data processing parameter to introduce the RFID chipless tag. Indeed, the major change of this technology is the absence of any chip IC connected to antenna. Consequently there is a radical difference in cost and performance between these two types. As a general rule, chipped tags are more expensive but they have a larger data capacity than chipless tags, also named "RF barcode". The cost of ICs has been a hurdle for the development of low cost chipless RFID to replace the optical barcodes. For these reasons, the realization of chipless tags constitutes a very attractive solution for specific or everyday life applications. The principle of the information encoding, which consists in encoding the identification number of the tag, is based on the generation of a specific temporal or frequency footprint. This temporal footprint can be obtained by the generation of echoes due to the reflection of the incidental pulse. In the frequency domain, one can characterize the spectrum of the backscattering pulse.

As the name indicates, RF barcodes are similar to optical barcodes not only in term of applications but also due to technical reasons: all of them could be fully printable. However, RF barcodes can be interrogated without having significant line of sight and orientation problems as exhibited by barcodes. It is why chipless RFID constitutes an emerging technology for ultra-low-cost RFID applications. However it is currently confined to the licensed radio frequency bands. To address this issue, the use of technology at higher frequencies (THz frequencies) could be beneficial.

For all these reasons, this paper discusses approaches and advances for chipless RFID tags. Section 2 is dedicated to chipless RFID configurations, while section 3 defines the bases of a new reading system and its design constraints. Then, section 4 will discuss the THz chipless possibilities. Some simulation results of newly proposed structures are reported.

2. Chipless RF Identification

There is a growing need of finding a substitute or a complementary solution to the optical barcodes. Researchers are then looking forward for a "chipless solution". As the name indicates itself, chipless RFID tags do not contain any chip and the data is electromagnetically coded in the amplitude or the phase of the sensing wave.

Various papers reported in literature are dealing with the amplitude approach. The basic technique consists in using resonators tuned to specific resonances. The RFID system in [3] is based on the wireless equivalent of optical barcodes. They consist of arrays of microstrip dipole-like structures that behave as resonant bandpass or bandstop filters tuned to predetermined frequencies. As multi bit read-only tags, the tagged item ID is determined from the presence/absence of a set of resonance frequencies using a bistatic measurement technique. Hence, with n barcodes in the field, $2n$ -1 items can be identified. A similar technique is mentioned in [4]. The RF barcode technique introduced here is also fully passive and presents a very low cost; it consists of identical arrays of capacitively-tuned microstrip dipoles, which absorb energy from a reader/interrogator. The tagged item ID is then determined from the presence/absence of a set of predetermined resonance frequencies.

In [5], a novel chipless RFID system based on multiresonators is proposed which perform frequency signature encoding. The 32 bit fully passive chipless RFID system uses both amplitude and phase of the spectral signature. This system uses a pair of orthogonally polarized dual wide band antennas for the transmission and reception of signals. A multi resonator circuit is used to encode the multi-frequency encoder signal from the antenna. By varying the dimensions of each of the spiral resonator, the corresponding frequency can be varied. The above mentioned technique requires reference for performing the amplitude and phase measurement of the signal. Since these methods are based on the amplitude of the received signal, they are prone to errors. This led to the development of Chipless RFIDs using the 'phase' of the signal to code data. Mukherjee et al. [6] has proposed a method based on the phase – frequency signature by the reactive termination of the tag antenna. A microstrip based L-C ladder is used to encode the bits in a phase – frequency profile.

Various printable chipless RFID tags with reduced cost are also reported in the literature. Inkjet printable 8 bit tags have been realized in [7]. This method uses a transmission line with capacitive discontinuities using SMT (Surface Mountain Technology) technology. Based on whether the capacitors are connected or not connected to the transmission lines reflections occur or not.

In this paper we propose a chipless RFID tag encoding data thanks to the frequency response of the reflected signal. Contrary to chipless approaches proposed up to now, the design presented in this paper does not contain any ground plane. Hence, this chipless RFID tag is fully printable and compact. So far, for clarity of explanation, we have considered a two bit chipless RFID. The geometry of the tag consists in association of multiple coplanar strip resonators making a 'c' shape as shown in Fig 2. It is to be noted that adding shorts at suitable positions of coplanar strips produces frequency shift for associated resonant modes. Finally, these shifts are used to encode data. The positions of the shorts are identified from simulations using CST Microwave studio. The frequency shifts are obtained by changing the shorts length at different locations of the tag thereby varying their configurations. Hence, the information contained in the tag can be unambiguously read.

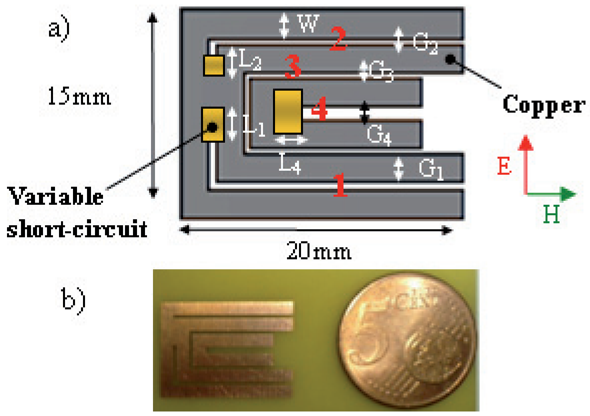


Fig. 2. Structure of the "C" tag,
a) schematic diagram,
b) picture of the "C" tag realized on FR4 substrate.

The tag response (see Fig. 3a)) presents four peaks corresponding to four resonant modes. Each resonant mode is produced by a coplanar strip resonator, and a link can be done between its resonance frequency value and its physical slot length nearly equal to quarter wavelength.

In this structure the modes 1, 2 and 4 can be changed independently. The mode 3 is due to interface between two pair of coplanar strips and is influenced by others modes, so it cannot be used for encoding. This method can be also easily extended to larger number of bits to produce tags with larger data storage capabilities. The key point of this approach is that the resonant frequency can be tuned by suitable filling of the slots. This technique can be applied to each of the slots and hence independent frequency tuning is possible for all the resonators in the structure. To verify this assumption, numerous simulations achieved with CST Microwave Studio using plane wave excitation, have been done and results are plotted in Fig. 4. For each plot, only one short length (1, 2 or 4) is modified at a time in order to verify that the three other modes remain at the same frequency locations. The length variations used are between 0 and 2 mm, to avoid any aliasing of nearest resonant modes. As a result, it is clearly shown that each mode is fully independent so that it can contribute to increase the coding capacity of the global design.

In Fig. 3b) c) d) the current distribution in slot 1, 2 and 4 for a given configuration is presented. Varying the length of the short produces changes in the current distribution within the tag, and thereby frequency shifts.

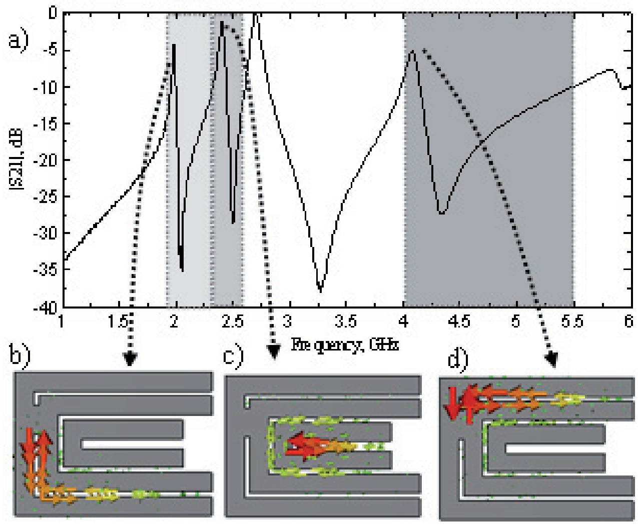


Fig. 3. Illustration of the link that exists between the resonant frequencies and the geometry of the "C" tag.
a) Amplitude of the tag backscattered signal versus frequency, the signal is normalized with the incident signal,
b) current density on the tag at 2.1 GHz,
c) current density on the tag at 2.55 GHz, and
d) current density on the tag at 4.4 GHz.

To make a link between the frequency location of each considered mode and the associated binary code, it can be defined a frequency span, and a frequency step for each one. In Fig. 5 a simple example of binary coding conversion operation depending on relative frequency shift is shown. For mode 1, a frequency span is set between 2 and 2.3 GHz with a step of 100 MHz, while for mode 2 a frequency span from 2.4 to 2.55 GHz, combined with a step of 50 MHz, is used.

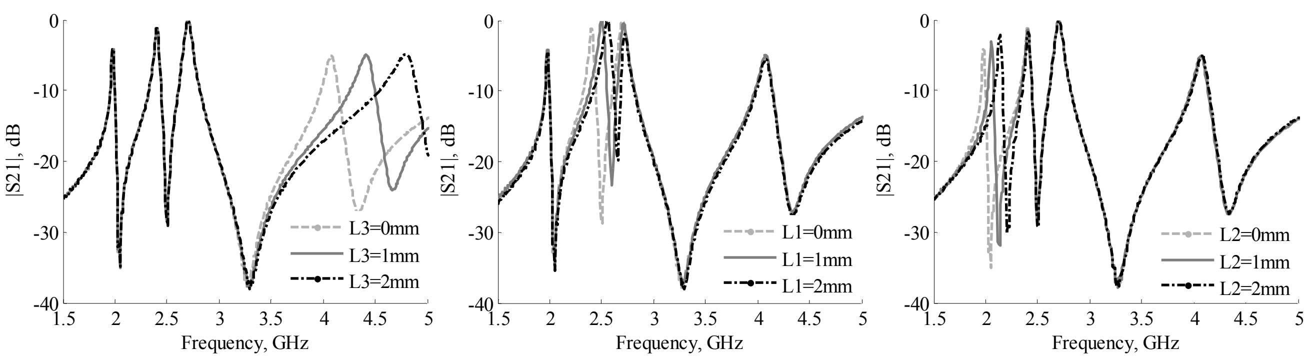
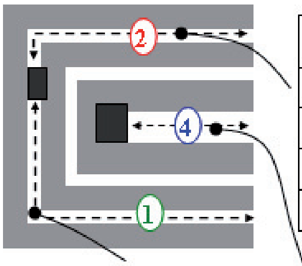


Fig. 4. Illustration of the operating principle of the "C" tag. These three curves show the amplitude of the tag backscattered signal versus frequency for three different lengths of the slot.

For mode 4, a frequency window between 4 and 5.2 GHz with a step equal to 400 MHz is used. Hence we get 4 quantified frequency values, i.e. 2 bits, for each resonator. For this simple example, the total coding capacity is 6 bits. Indeed, taking a frequency step of 50 MHz for all modes which is practically reachable corresponding to a readable channel separation, a short calculation gives a coding capacity close to 10 bits.

This coding capacity achieved for a compact size of 1.5x2 cm^2 is a very good result if comparing with performances attained by previous chipless tags designs. The "bit to square centimeter" ratio for our tag is 3.3, i.e. much larger than for tags presented in [3] (0.38 bit/cm^2) and [5] (0.6 bit/cm^2 for spiral resonators).



Frequency (GHz)	Binary code for slot n°2
2.4	00
2.45	01
2.5	10
2.55	11

Frequency (GHz)	Binary code for slot N°1
2	00
2.1	01
2.2	10
2.3	11

Frequency (GHz)	Binary code for slot n°4
4	00
4.4	01
4.8	10
5.2	11

Fig. 5. Illustration of the encoding principle based on the example of the "C" tag. The correlation table shows the relationship that can exist between the resonance frequencies of the tag and the associated binary code. Here an elementary code containing 6 bits is described. For example, to encode number 110110 produce resonances at 2.3, 2.45 and 4.8 GHz.

3. Reading System Consideration

The chipless tag design presented in this paper achieves some good performances in term of encoding capacity, unit cost and size. But as it can be seen in Fig. 4, to encode 10 bits in this case, a frequency span from 2 to 5 GHz is necessary. Obviously such bandwidth is not allowed for civil applications, which have to fit the ISM power mask. A possible way consists in using the recommendation for UWB communication [8]. The Power Spectral Density (PSD) defined for short ranges device has to be lower than -41.3 dBm/MHz from 3.1 to 10.6 GHz in USA, and from 3.1 to 9 GHz in Europe. To reach this value of PSD some very low duty cycle signals have to be used. Consequently, to design a reader FCC and ECC compliant, the use of Impulse Radio technology is mandatory.

To conclude, the rules on operating frequency and bandwidth are very constraining in this band. Thus, designing a reader having good performances is a hard task. To avoid these disagreements, a possible way is to design a chipless tag working in a much higher band like THz frequencies.

4. Towards Chipless THz Identification

Photonics crystals (PCs) are periodic structures and have attracted considerable attention in the last twenty years mainly because they exhibit ranges of forbidden frequencies for the propagation of electromagnetic waves [9]. Moreover, the PC behavior can be modified breaking the periodicity of the structure, leading to the creation of extremely narrow defect modes in the photonic band gap (PBG) [10], [11]. We propose to use these properties to fabricate a device for information encoding and identification applications. For that purpose, in this section, we propose a multilayer structure that encodes the information by the presence and/or the absence of defects modes at different frequency positions in the first PBG of a one dimensional (1D) PC.

The device consists in a periodical arrangement of two dielectric materials A and B that constitute a Bragg structure (see Fig. 6). We use six 75-µm thick high resistivity (resistivity ~ 5 kΩ.cm) 2-inches silicon wafers separated by 255 µm air gaps to fabricate the sample. The material has been chosen for its low losses and high refractive index in comparison with air (n_{si} = 3.415, n_{air} = 1), and for its non-dispersive behavior in the THz domain. The thicknesses of layers have been chosen in order to obtain a first PBG centered around 250 GHz. On the other hand, the number of layers has been chosen to get high band selectivity and dynamic: the larger the number of layers and the deeper of the PBG are, the steeper the band edges are.

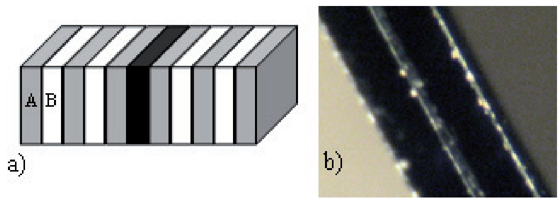


Fig. 6. a) Schematic of the 1D periodic structure with a structural defect at the central position (in black). b) Picture of half of the structure.

To create transmission defects modes in the PBG, we break the periodicity of the multilayer device, modifying one or several layers in the arrangement (see Fig. 6). The number and position of the defect modes in the PBG can be adjusted varying the optical thicknesses of some of these structural defects [11].

Fig. 7 shows an example of a 3 bit encoding using 3 defect modes in the first PBG of the 11 layers silicon-air structure. The binary codes are obtained by modifying the optical thickness of neither/either the central layer or/and its two contiguous ones.

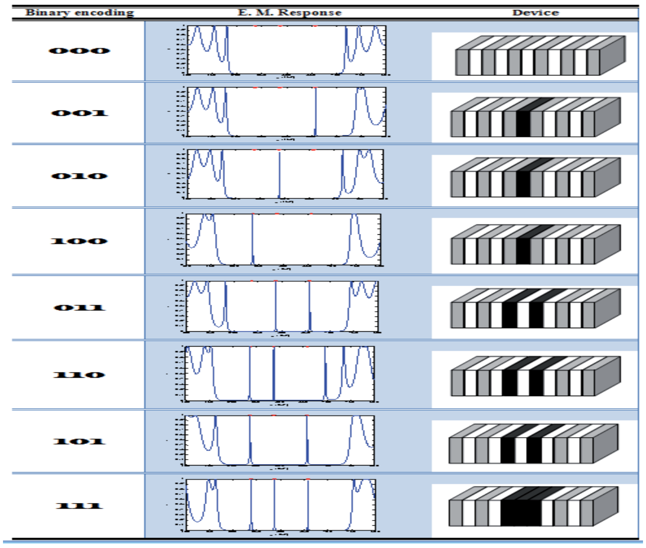


Fig. 7. Example of a 3 bit encoding using 1D photonic band gap structure: simulated spectral response (central column), device (right column) and 3 bit encoding (left column).

To characterize the device, we use a classical THz-TDS setup [12] based on LT-GaAs photoswiches, operated as emitting and receiving THz antennas, illuminated by 60-fs laser pulses @ 800 nm. A set of high resistivity silicon lenses associated with four parabolic mirrors is used to collimate and focus the THz beam. The device was measured in transmission at the focal point (THz beam diameter ~ 10 mm). As the temporal shape of the transmitted THz signal is measured during 150 ps, the frequency resolution is about 3.3 GHz. To vary the structural defect, the device was split in two PCs mounted on a translation stage - the gap in between can then be tuned from several tens of µm up to several mm.

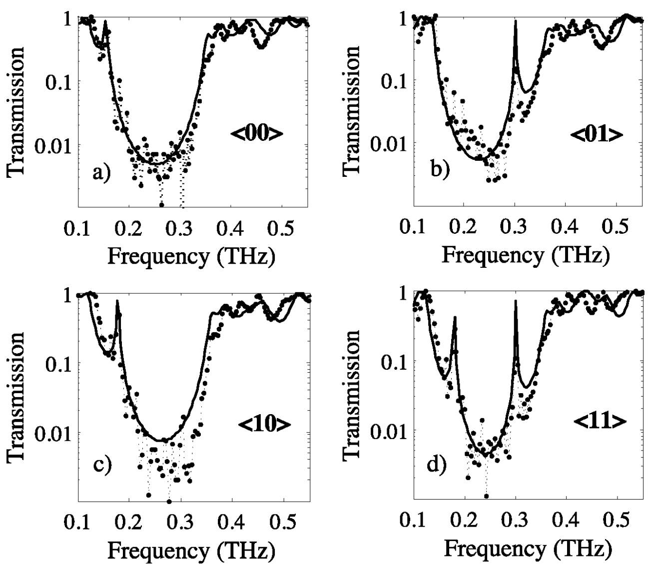


Fig. 8. 2 bit encoding using a single defect layer structure: calculation (continuous line), and experimental results (dotted line).

Fig. 8 shows the spectral THz field transmission of the device for four different thicknesses of the central layer: dashed lines with points represent measurements whereas continuous lines represent theoretical results, numerically calculated with the transfer matrix method [13].

We choose the gap thickness to obtain one or two defect modes at the two frequencies (184 and 301 GHz) in the first PBG. The agreement between experimental results and calculation is pretty good despite the 10% dispersion in silicon wafers thicknesses that explain the small disagreement for frequencies higher than 400 GHz. Such a device can then be used to code binary information, where a high level (1) is coded by the presence of a defect mode, whereas a low level (0) is coded by the absence of defect mode. Moreover, the level contrast between defect modes and floor level is about 10 (limited by the frequency resolution of the measurement) in amplitude corresponding to about ~ 20 dB. Such a value permits a non ambiguous detection.

The absence of defect mode in the PBG (see Fig. 8) corresponds to a "00" binary sequence. Therefore the three other configurations (Fig. 8) set for "01", "10" and "11" 2 bit encoding, respectively. The frequency width of the defect is about 4-5 GHz and is mainly limited by the frequency resolution of the THz-TDS setup. Nevertheless, with such a resolution, and taking into account the PBG bandwidth (about 150 GHz), 15 channels for information encoding should be available.

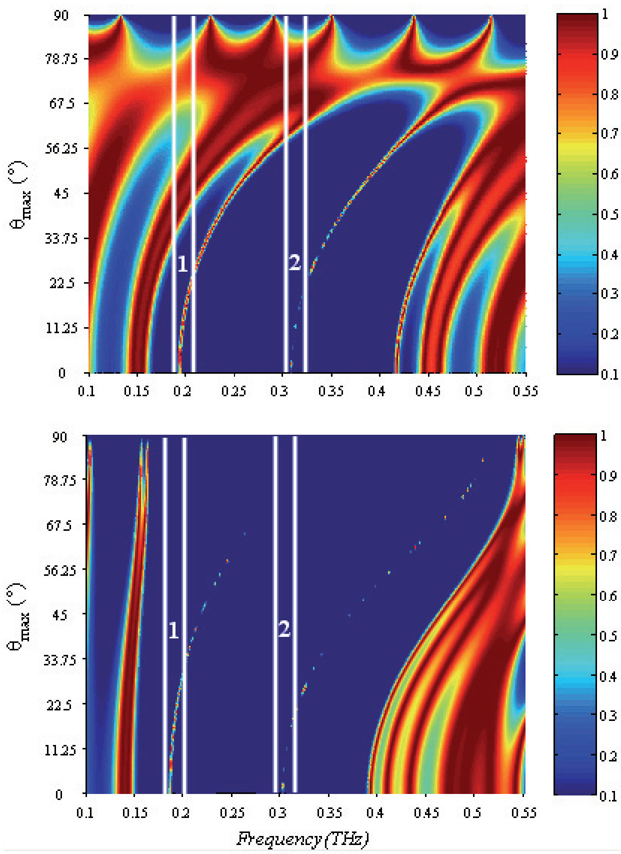


Fig. 9. Frequency shift of the frequency of the two defects obtain modifying the central layer versus incident angle θ under TM (a) and TE (b) polarization.

However, PC electromagnetic behavior, and defect modes frequency, both depend on the incident angle and on the polarization state of the illuminating THz wave. Fig. 9 presents the frequency shifts of the two defect modes of the <11> realized tag. In that case, we can notice that the frequency shifts reach 100 GHz under 50° incidences in both TE and TM polarization states. In other way, in the case of encoding information and considering for example a 20 GHz bandwidth channel (see channel 1 and 2 in Fig. 9) the device can be illuminated under a maximal angle of ~ 17° to prevent encoding corruption. The dispersion of the defect modes could strongly limit the application range of such device for information encoding.

It has been previously shown that such dispersion of the defect modes can be notably reduced by increasing the dielectric constant of the structural defect [14]. We show in Fig. 10 that the frequency shift of the defect mode in the first PBG can also be reduced by using structural defect on several layers of the PC, and not only on the central one. Indeed, in Fig. 10, we plot the maximal incident angle that can be considered under TM and TE polarization to maintain defect modes in their respective channels within the first PBG of our 11 layers silicon-air device. This maximal angle is plotted versus the number of channels for three different types of structural defects. Regarding these results, the incident angle can be greatly enhanced using a well chosen structural defect and can reach several tens of degrees.

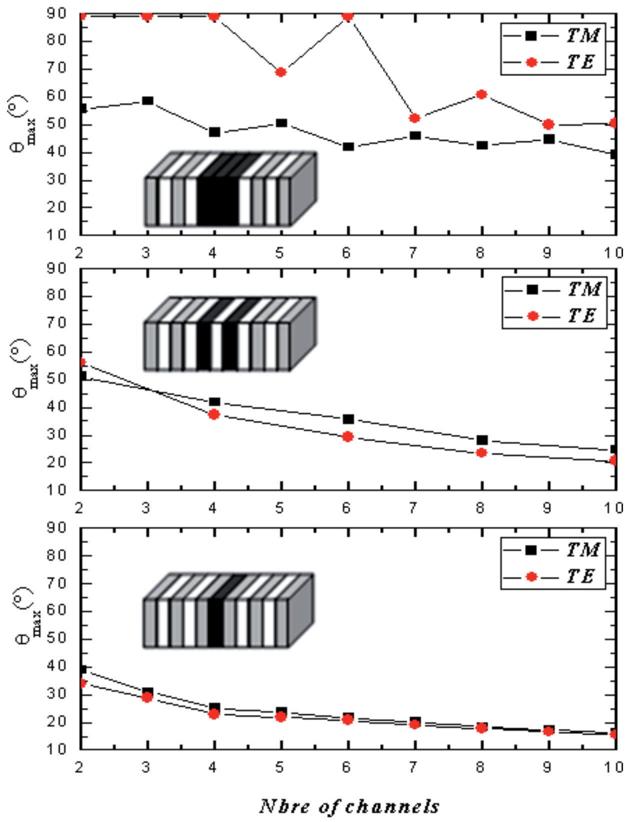


Fig. 10. Maximum incident angle for the reading beam of the THz tag versus the number of channel in the first PGB, under TM and TE polarization and for three different types of the structural defect.

5. Conclusions

RFID is very powerful technology worldwide considered in numerous applications and situations. To meet the wide variety of requirements and constraints, many categories and shape of tags have been developed. Among the most attractive solutions, chipless tags seem to be well adapted for low cost and data security purposes. The data storage limitations observed lead us to introduce a new generation of chipless tags. In particular, we have developed a new THz chipless tag approach where a multilayer structure is used for the data encoding in the volume and not only in the surface of the device, and THz signals are used to read it. Simulation and measurement confirm the two ways for storing and reading the information. RFID information coding leads to a memory capacity is 3.3 bit/cm^2 and THz information coding leads to about 10 bits coding capacity. In this last case the main problem to solve is to tune each different defect mode independently of the others. Considering the maximum angle under which the tag can operate, this maximum angle could be increased by changing the dielectric characteristic of the defect modes. Moreover, we show that it is possible to notably increase the maximal incident angle of the reading THz beam by using a well chosen structural defect in the periodic THz tag.

Acknowledgements

The authors would like to thank Guy Eymin-Petot-Tourtollet and Yann Boutant for their guidance and fruitful discussions on part of this work. The authors would also like to acknowledge the Grenoble Institute of Technology and the French National Research Agency for financially supporting this project via the BQR program the ANR-09-VERS-013 program respectively.

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About Authors

Etienne PERRET is an Assistant Professor in Electronic with the Grenoble Institute of Technology. He is authored and co-authored of more than 50 technical conferences, letters and journal papers, and of 1 book chapter. He is member IEEE and Technical Program Committee member of IEEE-RFID. His current research interests are in the field of wireless communications, especially radio frequency identification (RFID) with the design and development of antennas for RFID tags. His interests also involve advanced computer aided design techniques based on the development of an automated co-design synthesis computational approach.

Maher HAMDI is a PhD student at IMEP-LAHC in France. His research topic concerns the development of chipless tag working in THz domain under the supervision of Lionel Duvillaret and Frédéric Garet.

Arnaud VENA was born in Monaco. He received the Engineer degree from the Institute National Polytechnique de Grenoble (Grenoble-INP) in 2005. From July 2005 to September 2009 he worked as a R&D Engineer at ACS Solution France SAS, solution provider for the management of urban transport network. He was in charge of RFID Contactless card reader development and contributed to evolution of ISO/IEC 14443 regulation. Since October 2009 he is a PhD student at the Laboratoire de Conception et d'intégration des Systèmes (LCIS) in Valence, France, under supervision of Smail Tedjini and Etienne Perret. His current researches are mainly focused on design of RFID chipless tag.

Frédéric GARET is an assistant professor at Université de Savoie since 1998, he leads his researches in IMEP-LAHC laboratory where he is in charge of experiments on THz spectroscopy. He is currently working on THz identification technology and he participates on national and internationals contracts.

Maxime BERNIER received a master research degree in Matter and Radiation from the Burgundy University (France) in 2003, a master in Microwave and Optical Telecommunications from the University of Limoges (France) in 2004, and his Ph. D. degree in 2008 from the Institute of Microelectronics, Electromagnetism and Photonics (IMEP-LAHC) of Grenoble (France). After 1 year as a temporary professor assistant, he has been working as postdoc fellow within the laboratory of femtosecond spectroscopy at the University of Sherbrooke (Canada).

Lionel DUVILLARET is a professor at Université of Savoie. His researches are mainly focused on THz optoelectronics at IMEP-LAHC lab. Since 2007, he is in charge of PHOTO department, collecting activities on integrated optics (sensors, lasers) and THz optoelectronics. His current researches are mainly focused on Electrical field measurement based electro-optics technique, THz spectroscopy and THz identification. In 2009, he created the Kapteos Company to develop its technology.

Smail TEDJINI, Doctor in Physics from Grenoble University in 1985. Since 1996 he is Professor at Grenoble Institute of Technology. His teaching topics concern electromagnetism, RF, wireless and optoelectronics. He serves as Director of the ESISAR Eng. Dept. Past research concerns the modeling of devices and circuits at both RF and optoelectronic domains. He is the founder and past Director of the LCIS Lab. Now, he is ORSYS group leader. Current research concerns wireless systems with specific attention to RFID. He supervised 27 PhD and he has more than 250 publications. He is Member of several TPC and serves as expert/reviewer for national and international scientific committees like Piers, IEEE, URSI, ISO, ANR, OSEO, FNQRT… He organized several conferences/ workshops. Senior Member IEEE, President and founder of the IEEECPMT French Chapter, Vice-President of IEEE Section France and elected as the Vice-Chair of URSI Commission D “Electronics & Photonics” in 2008.