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An RF spectrometer for fast wide band measurement

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A new type of spectrum analyzer using RF interferometry is presented. The stationary wave integrated Fourier transform spectrometer is dedicated to the measurement of transient wideband signals. The spectrometer is mobile and cheap. It consists of spatial samplers placed along a waveguide ended by a short circuit. The standing wave caused by the short circuit is sampled and the spectrum is obtained by an FFT computation. A 0.3–5 GHz analyzer was built as a proof-of-principle demonstration and an application to RF dosimetry is shown.

Keywords: Quadratic detector, Interferometry, Schottky diode, Spectral analysis, UHF spectroscopy

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I. INTRODUCTION

Wide band spectral analysis becomes more and more necessary for instant signal measurement. It is the case for the ultra wide band (UWB) standard, cognitive radio, electromagnetic compatibility, or RF dosimetry. The user needs non-expensive instruments that enable instantaneous measurement with a broad coverage of the frequency bandwidth. For instance, in the domain of assessment and management of the radioelectric spectrum, no mobile equipments giving instant information of a wide spectrum (i.e. further gigahertz band with a resolution of one megahertz in less than 10 ms) are available [1, 2]. RF dosimetry is also a good example of the actual need: many citizens would like to measure and verify by themselves the RF field radiating around them, but the sensors are either too much expensive or incapable to give instant information of a large band of frequency [3, 4].

As an alternative to existing measurement systems, a new spectrum analyzer based on RF spectrometry has been developed. This instrument is called stationary wave integrated Fourier transform spectrometer (SWIFTS) and it enables the mobile instant analysis of a wide band spectrum at a low cost. The SWIFTS described in this work is 16 cm long and 1.5 cm wide. Its operating range is stretched from 300 MHz to 5 GHz. First, the principles and design stages of the spectrometer are shown. Second, measurement and characterization of the SWIFTS are reported. Finally, the SWIFTS is presented as a possible dosimeter.

As an historical review, many applications relied on the same principles as the SWIFTS. It is based on the wave interferometry used by Lippmann one century ago. His method for reproducing colors in photography, based on the interference phenomenon, gained him the Nobel Prize for Physics for 1908 [5]. In 1960 Blum proposed a similar system using analogic correlation [6]. However, at that time, the computational power was not enough developed to calculate spectrum characteristics and to give satisfactory results. In 2001, Harris demonstrated an analog correlator showing good results [7]. This instrument was efficient but too much complicated due to the presence of several multiplicators in the design.

Williams introduced in 1989 in his Ph.D. thesis sampled-transmission line architectures similar to the SWIFTS and dedicated to the six-port reflectometry [8].

Recently, Le Coarer and Benech proposed the SWIFTS, a new type of integrated interferometer that adopts standing waves instead of auto correlation [9]. This spectrometer is currently being designed for many spectral bands: the 22 GHz water vapor absorption band [10], the UHF band (present work), the THz band (still in progress), and for optical applications [11, 12].

II. DESIGN

In the RF SWIFTS, the signal under analysis is guided in a microstrip waveguide ended by a short circuit, where the electromagnetic wave is reflected and retraces it steps, interfering with itself. A stationary wave, with maxima and minima, is present along the waveguide (Fig. 1(a)). This wave contains all of the spectral information of the unknown signal. One just needs to sample this wave to recover the information. This sampling is realized by means of an array of spatial sampler cells. The cell detailed in Fig. 1(b) fulfils three functions: matching, sampling of the wave present along the waveguide, and measurement of its power. The quadratic Schottky power detector converts RF power into DC voltage, which is sampled by means of an analog digital converter (ADC). The information from each sampling cell is stored as a computer database. A fast Fourier transform (FFT) analysis is performed to obtain the spectral information of the unknown signal. The constant sampling step used in the SWIFTS does not necessitate any other transformation of the data.

A photograph of the UHF SWIFTS built with 32 sampling cells is shown in Fig. 1(c). The central periodic sampler array is 16 cm long (from cell 1 to cell 32). From each side of the detection structure, a 50 Ω impedance microstrip line is fed through a *Johnson Components*^{TM} SMA End Launch

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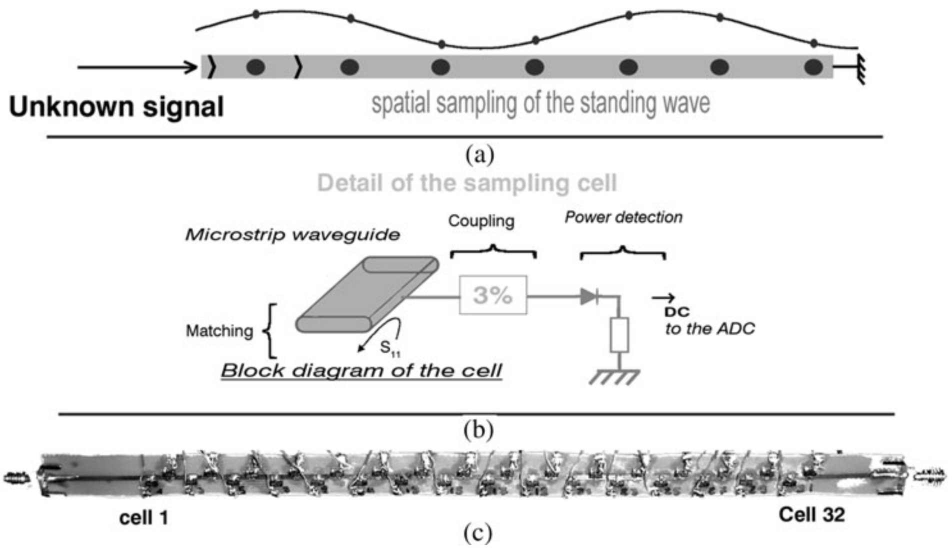

Fig. 1. (a) General diagram of the sampling principle. (b) Block diagram of the spatial sampling cell. (c) Photo of the UHF SWIFTS presented here, based on a FR4 substrate (Avago diodes HSCH 2850 and SMC resistor of 1.9 kΩ).

Connectors. Figure 2 displays a zoom in on a few cells. The cell is constituted of an *Avago* HSCH2850 Schottky diode packaged in a SOT23 body and a low-cost *Multicomp* MC 1% series thick film chip 1910 Ω resistor packaged in a 0603 SMT case. A 200 μm copper wire connects the cathode of the diode to a *National Instrument* 250 kS/s USB-6225 ADC of 16 bits 80 analog inputs.

The SWIFTS can be seen as a waveguide periodically loaded by identical cells. In this configuration, the spectrometer design can be limited to a unique sampling cell. As displayed in Fig. 1(b), the cell function can be divided into three parts that can be studied separately: the cell matching, the coupling optimization (the coupling of the energy from the microstrip waveguide to the power detector), and the quadratic detection. Those three parts are presented in the following subsections.

A) Cell matching

S_{11} of the unit cell is the most important parameter for periodic structures. If the matching is not well designed, the cells will disturb each other and the general functioning of the structure will be damaged. As the spectrometer is designed for RF dosimetry purpose, the S_{11} was optimized for the frequency of 900 MHz, 1.8 GHz, and 2.45 GHz.

B) Coupling design

The role of the cell is to sample the standing wave along the main waveguide. RF energy is coupled to the power detector according to a coupling factor. In this configuration, the coupling factor acts upon the general spectrometer efficiency (Fig. 3): if this factor is too low ({C} area), no energy will get to the quadratic detector; if the coupling factor is too high ({A} area), the incident wave of the unknown signal will not reach the RF mirror, and there will be no stationary wave along the waveguide.

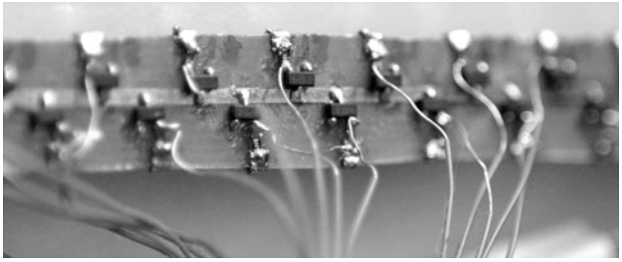

Fig. 2. A zoom in on a few cells of the UHF SWIFTS.

The best coupling factor was analyzed and calculated in a previous work [10]. The efficiency of the spectrometer depends on the number of cells placed along the waveguide. The number of 32 cells was chosen with the aid of [10] and for FFT computation reasons (2^5).

The *Agilent EEsoft EDA* Advanced Design System *2004A* was used to design the cell (Fig. 4). The *Avago* diode model [13] was used in both *AC* and *S* parameters simulations.

Firstly, the design was done using the methodology published in [10] and resulted in a stub-like matching: the length *L* of the microstrip line connecting the central waveguide to the power detector is 9.8 cm long.

Results are shown in Fig. 5. The matching (S_{11}) is acceptable for the frequencies listed above (S_{11} lower than −15 dB). The simulated coupling factor is the ratio between the power that goes through the diode and the input cell power. For dosimetry frequencies, the coupling factor is located in the {B} area, which insures a good functioning of the instrument.

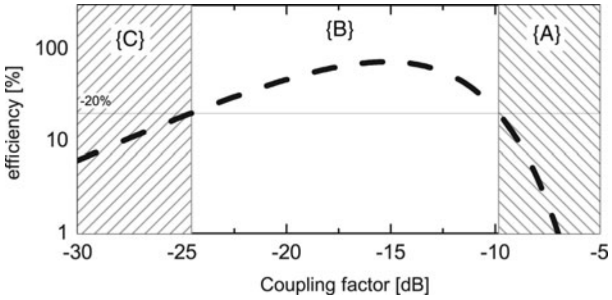

Fig. 3. Internal efficiency for 32 detector cells (dashed line). The 20% solid line is the minimum efficiency for accurate operation of the spectrometer ({B} area). {A} and {C} areas point an excessively low or high coupling factor that will prevent the spectrometer from functioning.

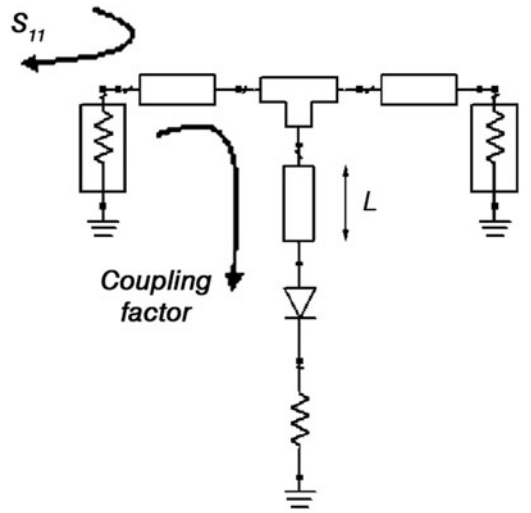

Fig. 4. Functional block diagram of the sampling cell.

C) Cell optimization for periodic structure implementation

In spite of the acceptable behavior shown in Fig. 5 for few frequencies, the narrow band matching due to the "stub effect" is not satisfactory. Because of the S_{11}, the periodic structure has a "Bragg effect" at many frequencies.

Furthermore, disposing the cells side by side will cause electromagnetic crosstalk. In a SWIFTS periodic structure, the cells are placed every 0.49 cm. In the designed cell, the microstrip line between the main waveguide and the diode is 9.8 cm long (Fig. 6(a)). Considering such a configuration, the crosstalk will be so strong that the SWIFTS would have a very poor spatial resolution.

The solution proposed in this work is based on the alternative shown in Fig. 6(b): the diode detector is placed directly on the main microstrip waveguide. With such a configuration, less parameters are used for the design of the cell, but this is resulting in the suppression of the crosstalk and in a small change of cell behavior with frequency (the first resonant frequency is over a few tenth of gigahertz in this case).

The results of the new design using this alternative are shown in Fig. 7. Matching of the cell (in solid line) is excellent (lower to -30 dB), with a coupling factor (in dashed line) which progresses more slowly than the one shown in Fig. 5 (from -18 to -10 dB from 300 MHz to 5 GHz). This wide band homogenous behavior is near to the ideal coupling factor. Moreover, the short length of the diode detector produces no resonance in this band. Optimization of the coupling factor was done using the resistor as a parameter. Figure 7 displays results for a 1910 0603 resistor.

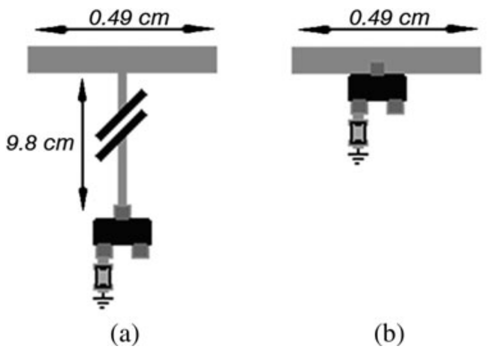

Fig. 6. Comparison between the first design alternative (a) and the second one without the "stub effect" (b).

D) Power detection design

The core of the instrument is the power detection. As seen below, the cells contain a Schottky diode detector that presents excellent uniformity in its square law transfer characteristics. The following simulation was performed with the non-linear *ADS* harmonic balance simulation in order to evaluate the uniformity slot of the cell. Table 1 describes the spice parameters of the diode that were used for the ADS circuit simulation.

The best results of the Schottky diode detector are obtained with bias [14]. In our case, the cell must be as simple as possible; adding bias components would damage the RF behavior of the cell. The chosen diode was the *Avago* HSMS 2850, used in a zero-biased configuration [15].

Figures 8 and 9 show the output DC voltage of the Schottky detector. The simulation is performed in the same conditions as the ones of Fig. 4 (input power on port 1 and $50\ \Omega$ load on port 2). It is noticeable in Fig. 8 that the detector stops to follow the square law around 0 dBm. It is clear that the behaviors seen in Figs. 8 and 9 are not flat whatever the frequency is, but a global calibration of the system would enable to level out the frequency-dependant voltage.

Moreover, the diode non-linearity around 0 dBm, between the quadratic and peak detector zones, is also overcome by the calibration step.

III. MEASUREMENTS

The SWIFTS was built out of the 32 detector cells along a microstrip waveguide on a FR4 substrate (Fig 1(c)). A brief description of the setup is illustrated in Fig. 10. The SMA short circuit

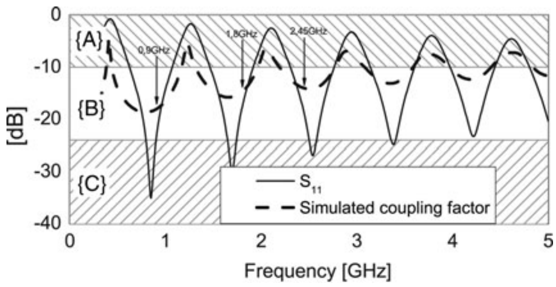

Fig. 5. $S11$ from ADS circuit simulations (solid line) and simulated coupling factor (dashed line). {A}, {B}, and {C} areas are the same as in Fig. 3.

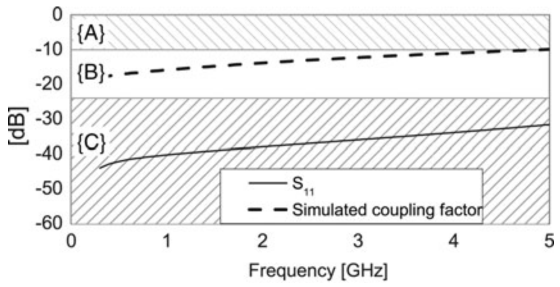

Fig. 7. $S11$ from ADS circuit simulations (solid line) and simulated coupling factor (dashed line). {A}, {B}, and {C} areas are the same as below.

Table 1. Spice parameter of the diode HSMS2850.

Diode model HSMS285x [13]		
Is	3×10^{-6} A	Saturation current
Rs	25 Ω	Ohmic resistance
N	1.06	Emission coefficient
Cjo	0.18×10^{-12} F	Zero-bias junction capacitance
Vj	0.35 V	Junction potential
M	0.5	Grading coefficient
Bv	3.8 V	Reverse breakdown voltage
Ibv	3×10^{-4}	Current at reverse breakdown voltage
Xti	2	Saturation-current temperature exponent
Eg	0.69 eV	Energy gap

permitted the standing wave operation. A 50 Ω coaxial waveguide of 29 cm length is connected between the spectrometer and the short circuit. The measurements were done after the diodes calibration, as explained above, for each of the 32 samplers.

The measurement described here was performed thanks to an Agilent 83711B generator. Figure 11 displays the DC voltage out of every 32 spatial samplers for an input signal of 930 MHz at 0 dBm.The *X*-axis specifies the distance from the short circuit. The shape of the standing wave is obvious even if a calibration would ameliorate the results.

The spatial period of the stationary wave gave the opportunity to check the propagation characteristics and to get the effective dielectric constant (ϵ_{eff}) that was here (at 930 MHz, according to Fig. 11) almost equal to 5 while the effective permittivity of the microstrip line was only 3. This effect is due to a slow-wave behavior that had already been investigated on periodically charged waveguides [16–18].

In order to evaluate the spectral performance of the SWIFTS, an FFT of the standing wave was computed. The spectrum was calculated with FFT interpolation using a rectangular window. Figure 12 shows the spectrum of the interference depicted in Fig. 11. Figure 12 also illustrates a spectrum obtained for standing waves, which is the result of an input signal of 5 GHz.

It is clearly shown that when the frequency is getting high, the spectral performance is deteriorating. This effect is caused by the parasitic effects of the surface-mounted components (diode [13] and resistor [19]). Lower parasitic effect and upper working range will be obtained with smaller SMC.

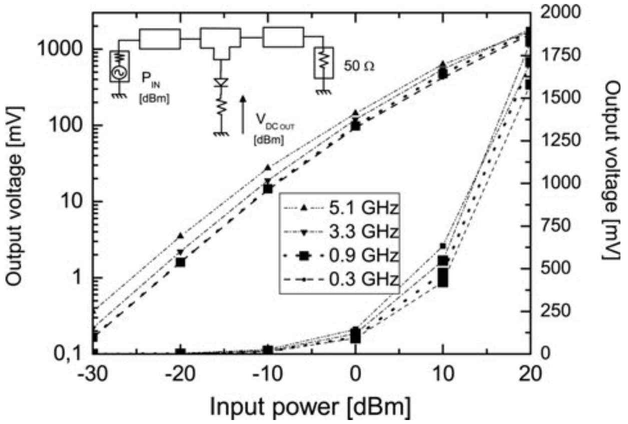

Fig. 8. Output DC voltage from ADS circuit simulations of the cell for different input frequencies: 5.1 GHz (dashed dotted dotted line), 3.3 GHz (dashed dotted line), 900 MHz (dotted line), and 300 MHz (dashed line). The curves are plotted in log and linear scale.

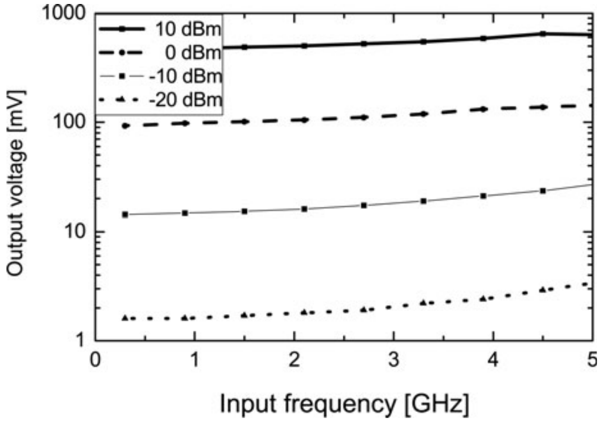

Fig. 9. Output DC voltage from ADS circuit simulations of the sampling cell for progressive input power (−20 to 10 dBm).

A) Dosimetry application

Many wireless setups are installed in human surroundings (microwave ovens, Bluetooth or UWB connections, radars, WiFi modems, mobile phones, TV transmitters, WiFi game controllers, RFID, lightning systems, PC, ISM bands, telecommunications base stations, and broadcasting antennas). Except for lightning systems that are near 100 MHz, the frequency range of all these systems typically ranges from 433 to 2500 MHz. The emission bursts are mostly concentrated on a few hundreds of microseconds. This has led to many questions in the scientific community on possible human health effects of all these electromagnetic radiations in our environment.

Dosimetry allows long-term analysis (and if possible, broadband analysis) of the power measured at several points of a given area. Measurement protocols are normalized and they consist in point to point measurement by means of E-meters (the measurement is then integrated on a given band) or spectrum analyzers (the frequency is swept). Currently used E-meters cover RF bands while they suffer low-frequency resolution and time sampling, which is usually too long. At the same time, currently used heterodyne spectrum analyzers present better frequency resolution but the sweeping of the frequency is too slow to obtain real-time pictures of the spectrum.

The SWIFTS offers the advantage of a fast broadband behavior (no sweeping) and long-term recording of the spectral information: actual ADC converters performances lead to a sampling time lower than 1 ns. This could be useful for fast RF

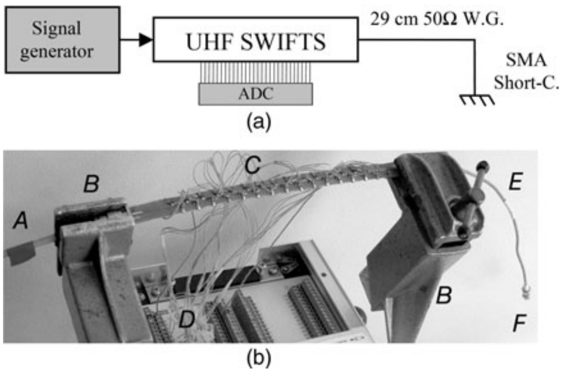

Fig. 10. (a) Measurement setup of the UHF SWIFTS. (b) Photograph of the set up. A represents the feeding coaxial cable, B the fixing, C the UHF SWIFTS, D the ADC, E the output coaxial cable, F the SMA short-circuit.

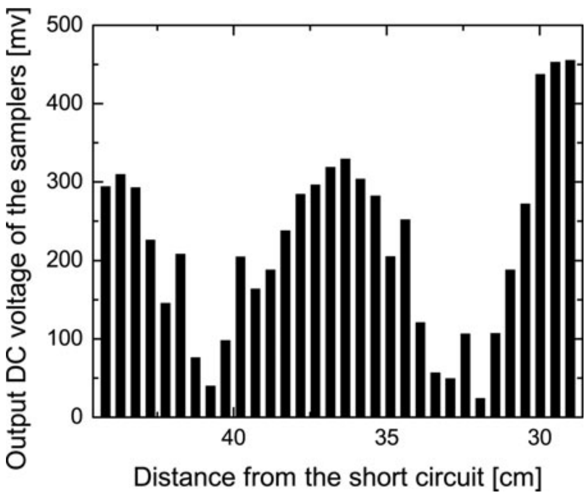

Fig. 11. DC voltage of the 32 samplers placed along the standing wave.

broadband dosimetry and could allow the user to avoid the interpolation step in the determination of the field map of an area.

In order to evaluate the SWIFTS performances in the frame of RF dosimetry applications, a test has been performed to illustrate the SWIFTS properties for the detection of fast transient signals as the measurement of a WiFi transmission. A matched antenna has been connected to the SWIFTS input and the received signal is recorded in real time. Results are shown in Fig. 13(a) with a time–frequency chart displaying the FFT of the interference created in the UHF SWIFTS. Thousand recordings were done for 128 ms. The darker the line, the higher the amplitude of the frequency harmonic obtained from the FFT of the detected voltages. For better understanding, a zoom in of the chart is given in Fig. 13(b) between 4 and 7 ms. The same information is shown in Fig. 13(c) as overlaid curves.

It is clear that even if the FFT gives a pick at 2.45 GHz, another pick is present at 400 MHz. This is due to the unleveled detectors cell, and can be completely avoided with a correct calibration.

IV. CONCLUSION AND PERSPECTIVES

The speed of the spectrometer is limited only by the physical time coherence of the measured signal. Coherence describes all correlation properties between physical quantities of the forward and reflected waves. It means that the SWIFTS principle is quasi-real time because it needs only twice the time period of a signal to make a measurement (round trip wave time). For instance, if a 300 MHz signal needs a 6.7 ns time measurement, a 5 GHz signal can be sampled in less than 0.4 ns.

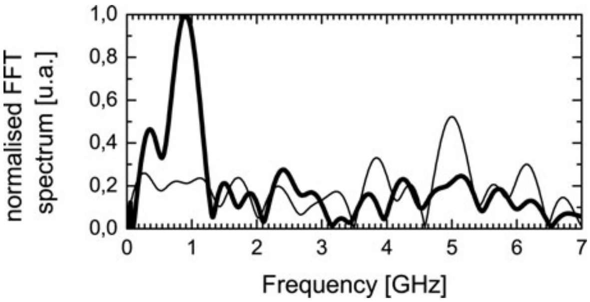

Fig. 12. FFT of the interference shown in Fig. 11 (bold solid line)) and 5 GHz signal (solid line).

That is why nowadays the SWIFTS performances are only limited by ADCs. ADC is the limiting part of the spectrometer speed that defines which transient signal may be considered. The best configuration is to use an ADC for each of the sampling cells, but a multiplexed ADC can also be used (compromise between acquisition time and cost).

For better results, a calibration of the whole system can be performed. The calibration has to take into account the power

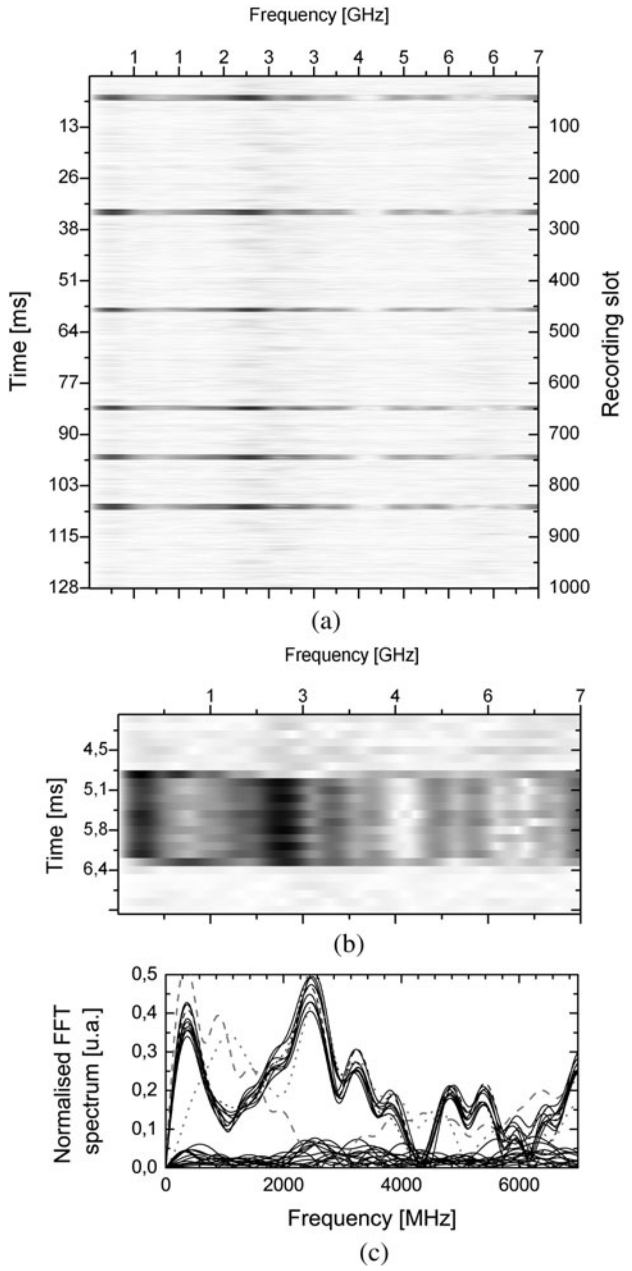

Fig. 13. (a) Time–frequency chart of a measurement during a WiFi transmission. The figure shows FFT of the interference created in the UHF SWIFTS. The color is as dark as the spectral density. During the transmitted frames, the maximum spectral density is situated at 2.45 GHz. (b) Zoom in on the time–frequency chart (first frame: from 4 to 7 ms). The curves can be classified in three categories: the noise (before 4.9 ms and after 6.3 ms); the useful information with maximum power at 2.45 GHz (between 4.9 and 6.3 ms); and the transitional measure (at 4.9 and 6.3 ms, displayed in Fig. 13(c) in dashed and dotted line). (c) Same information as shown in Fig. 13(b) but in another displaying mode (25 curves superposed without time).

and frequency behavior of the spectrometer. The SWIFTS calibration procedure consists of applying a known source signal and measuring the output voltage of each of the detectors. Then, a compensation calculation is done to level out the transfer characteristics of the spectrometer.

Another great improvement can be done in the field of the spectral resolution. Since the spectral resolution is limited by the total length of the spectrometer, a larger electrical length can be used in the future with a longer SWIFTS and a higher permittivity of the waveguide. Furthermore, an appropriate signal processing can improve spectral information recovering.

V.SUMMARY

A new spectrum analyzer was designed and the first characterizations were done. This mobile low-cost spectrometer gives instant information on a wide band frequency (300 MHz–5 GHz). The SWIFTS uses an array of spatial samplers placed along a standing wave. Further work will permit to improve the spectral resolution of the instrument and the upper frequency operation.

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