20 GHz instantaneous bandwidth RF spectrum analyzer with high time-resolution

Perrine Berger, Muriel Schwarz, Stéphanie Molin, Daniel Dolfi, Loïc Morvan
Thales Research and Technology
1 av. Augustin Fresnel, 91767 Palaiseau, FRANCE

Anne Louchet-Chauvet, Thierry Chanelière, Jean-Louis Le Gouët
Laboratoire Aimé Cotton, CNRS-UPR 3321
bât. 505, 91405 Orsay, FRANCE

***Abstract*—We report on the experimental demonstration of a multi-gigahertz bandwidth RF spectrum analyzer exhibiting a resolution below 20 MHz, based on spectral hole burning in a rare-earth ion-doped crystal. To be compatible with demanding real-time spectrum monitoring applications, our demonstrator is designed to reach a high time resolution. For this purpose, we implemented the so-called "rainbow" architecture in which the spectral components of the incoming signal are angularly separated by the crystal, and are then acquired with a pixelated photodetector. The Tm^{3+}:YAG crystal is programmed with a semiconductor DFB laser which frequency scan is servo-controlled and synchronized with the angular scan of a resonant galvanometric mirror, while a high-speed camera is used to acquire the spectra. In the perspective of future implementation within a system, the crystal is cooled below 4 K with a closed-cycle cryostat. With this setup, we have been able to monitor and record the spectrum of complex microwave signals over an instantaneous bandwidth above 20 GHz, with a time resolution below 100 µs, 400 resolvable frequency components and a probability of intercept of 100 %.**

Keywords*—Analog optical signal processing, spectrum analysis, broadband microwave spectrum monitoring, spectral hole burning.

I. INTRODUCTION

The more and more complex signals emitted by modern RF sensing and communication systems make the availability of broadband and real-time microwave spectrum monitoring tools crucial. Indeed, from few tens of megahertz to few tens of gigahertz, the microwave spectrum is now occupied by frequency-hopping and bursting signals which time-frequency characteristics are almost impossible to analyze with standard swept spectrum analyzers. To ensure a large coverage of the spectrum with 100 % probability of intercept, the most stringent applications need an instantaneous analysis bandwidth of at least several gigahertz, far from the capabilities of most recent digital real-time spectral analyzers offering only few tens of megahertz. The solution consisting in digitizing the full spectrum is highly challenging due to the high data rate to be handled, the large computational resources required to provide the spectra through FFTs, and its performances are limited by the poor characteristics of broadband ADCs in terms of dynamic range [1, 2]. In this context, alternative solutions are welcome.

In the optical domain, Spectral Hole Burning (SHB) in rare-earth ion doped crystals (REIC) makes particularly attractive to process broadband signals with impressive time-bandwidth product, since their inhomogeneously broadened absorption bands can reach 200 GHz bandwidth, while presenting a spectral resolution below 10 kHz at low temperature [3]. Various optical functions have been demonstrated in REICs, such as cross-correlation analysis of RADAR return signals [4, 5], true-time delay generation for radar application [6], analog-to-digital conversion [7] and more recently, time reversal of microsecond-long RF signals [8].

For wideband microwave spectrum analysis, two main architectures have been proposed.

In the first approach, the spectrum of the microwave signal of interest is converted into the optical domain and then recorded in the SHB material, which is used as a spectral memory. One then has several milliseconds – the memory lifetime – to retrieve the signal components with a fast sweeping read-out laser. This approach is extensively studied for the spectrum analysis of broadband RF signals over 20 GHz, with sub-MHz resolution and sub-millisecond refresh time [9-13], and has even been upgraded to direction finding [14, 15]. To reach higher time resolution, this architecture faces two limitations. First, the signal remains present in the crystal for few milliseconds. Second, a post-detection recovery algorithm is necessary to reduce the read-out time t_{res} while preserving the spectral resolution $\delta\nu_{res}$ [16]. Even though, these parameters remain fundamentally linked to the detection bandwidth $\delta f_{\det}$ and the instantaneous analysis bandwidth Δf by the relation:

$$\delta f_{\det} \cdot t_{res} = \frac{\Delta f}{\delta\nu_{res}} = N, \tag{1}$$

N being the numbers of resolved spectral channels. Assuming a reasonable processing bandwidth of 100 MHz, time resolution in the few µs range would lead to a resolution in the range of tens of MHz over a 20 GHz bandwidth, while leading to severe constraints on the chirp rate of the read-out laser.

In the second approach, the so-called "rainbow" architecture, the signal is no more recorded in the crystal. Spectral hole burning process is used to store, over the desired bandwidth, a processing function that is designed to angularly separate the spectral components of the signal. These components are then easily acquired with a pixelated photo-detector [17-19]. Up to the standard Fourier limit, the time and

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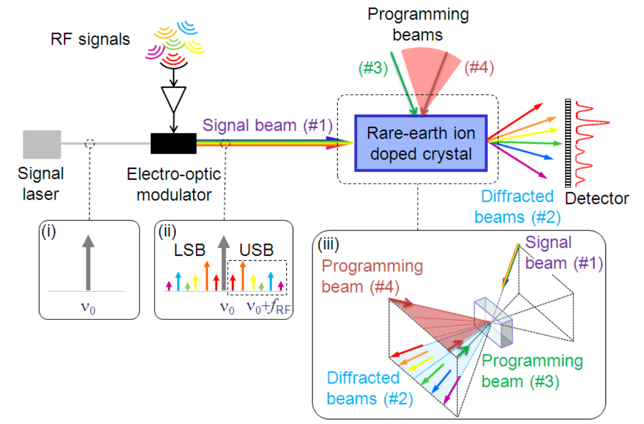

Fig. 1. Principle of the rainbow architecture. The crystal diffracts the spectral components of the microwave signals in different directions thanks to the programmed processing function stored in the crystal. The inserts (i) and (ii) respectively depict the spectra of the cw laser and the modulated laser with the lower sideband (LSD) and upper sideband (USB). (iii) shows the counter propagating box geometry of the four beams which enables to simultaneously program the crystal and to diffract a third polychromatic beam.

frequency resolutions are then linked by independent parameters, as it will be further detailed in this paper.

The last reported demonstration of the rainbow architecture was limited to a bandwidth of 3.3 GHz with a 33 MHz resolution (100 independent frequency channels), and a time resolution of 10 ms, limited by the photodetector [20]. Moreover, due to the use of a single laser for crystal programming and signal analysis, the probability of intercept was only 50%.

The objective of the present work was then to demonstrate that this architecture is able to operate over a 20 GHz bandwidth with a probability of intercept of 100 %, an improved frequency resolution and a much shorter time resolution. Another requirement was the use of a closed-cycle cryostat for crystal cooling, and only off-the-shelf optoelectronic components, in the perspective of integration in a real system. In the following, after recalling briefly the operating principle of the rainbow analyzer, we detail how we implemented this architecture to reach the above mentioned performances. The results of the analysis of wideband microwave signals is then presented and discussed.

II. Description of the Experiment

A. Principle of the rainbow architecture

The principle of the rainbow architecture is depicted in Fig. 1. The investigated microwave signals are transposed on a cw optical carrier thanks to a Mach-Zehnder electro-optics modulator. The sidebands of this polychromatic beam (#1) is then composed of the spectral components of the RF signals (see insert (ii) of Fig. 1). The SHB material, once programmed, is able to convert spectral content into spatial angle information over a specified spectral region, which matches the upper (or lower) sideband. The spectral components of the microwave signal are then diffracted and simultaneously retrieved in different directions. An array photodetector detects the diffracted beams (#2) and records the spectrum of the microwave signals.

The physical principle of the SHB material programming is well described in [18]. It relies on spectral hole burning and simultaneous engraving of monochromatic gratings in a rare-earth ion-doped crystal (REIC) cooled at low temperature (<5 K). The REIC is illuminated by two programming beams (#3 and #4) issued from the same laser whose frequency is scanned over the required bandwidth of analysis Δf of the spectrum analyzer. The beam #3 is also angularly scanned in synchrony with the frequency scanning. Consequently, the beams #3 and #4 engrave a set of monochromatic Bragg gratings, and burn associated spectral holes in the absorption profile of the REIC: each diffraction angle is then associated with a specific spectral component. A large number of gratings can coexist within the inhomogeneous width of the absorption line of the REIC, which may reach tens of GHz. The spectral selectivity of these gratings is defined by the width of the associated spectral holes, which ultimately match the homogenous width of the REIC (which may reach 10 kHz at low temperature in some REIC [3]). The programming has to be refreshed at least every 10 ms, corresponding to the lifetime of the populations. The insert (iii) of Fig. 1 shows the counter propagating box geometry which enables to simultaneously program the crystal and to continuously diffract the signal beam (#1). This geometry is necessary for a continuous spectral analysis of the investigated microwave signals.

B. Hardware overview

The building blocks of the experimental set-up are presented in Fig. 2. The REIC is a 0.5% thulium-doped YAG crystal, cooled at 3 K by a closed-cycle cryostat. The absorption line of the cooled crystal, centered at 793 nm, exhibits an inhomogeneous width larger than 20 GHz. The signal block is composed of an external cavity laser and a 20-GHz bandwidth intensity modulator. The main component of the detection block is a CMOS line camera with a high frame rate (up to 10 kHz). This frame rate will correspond to the refresh time of the spectral analyzer.

The programming of the crystal is one of the major issues of this experiment. The angular scan of the programming beam #3 is performed by a resonant scanning mirror, operating at 2 kHz, whose stability is compatible with the requirements of the experiment [21].

The programming laser, operating at 793nm, has to scan over 20 GHz within 250 µs in synchrony with the sinusoidal angular scan, with a linewidth smaller than the required

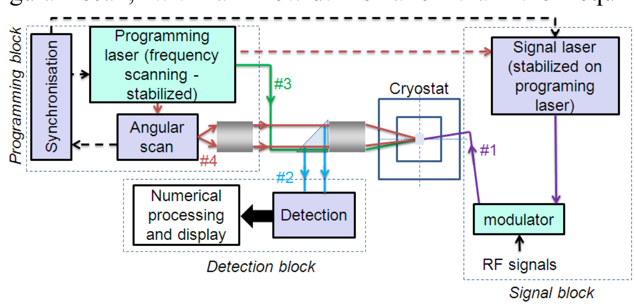

Fig. 2. Building blocks of the experimental set-up.

spectral resolution of the analyzer. Moreover, the wavelength of the signal laser has to be stabilized on the programming laser. Consequently, the sweeps of the programming laser, which exhibits rapid and abrupt variations of the optical frequency, has to be precisely controlled. We used a self-referenced laser frequency stabilization scheme, compatible with high frequency agility. This technique has been proposed and demonstrated for high linear chirp by several research groups [22-24]. This scheme is based on phase-locked loop detection of a fiber-interferometer-derived heterodyne beat signal. An example of implementation is illustrated in Fig. 3. The output of the tunable laser is split using an acousto-optic modulator (AO). The first order beam travels through a fiber delay line (introducing a delay τ) and is shifted in frequency by $f_{AO} = 80$ MHz . The zeroth-order beam is not delayed and is split into two unequal portions by a fiber splitter: 10% is used for the control of the sweep and 90% corresponds to the output of the laser, used for out-of-loop measurement or for the dedicated application. The zeroth-order and the delayed and shifted first-order beams are recombined interferometrically using a fiber combiner and detected by a photodiode (PD). The output of the PD is mixed down using a reference signal. The measured error is then amplified and integrated with a proportional-integrator (PI) filter and injected into the tunable laser. A control voltage is added to the laser input in order to set the nominal optical frequency sweep.

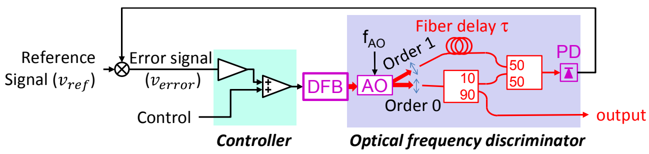

Fig. 3. Control and stabilization set-up of broadband arbitrary frequency sweeps. Abbreviations are defined in text.

If the frequency sweep is a linear chirp, the frequency of the reference signal is then fixed. In our experiment, as the programming laser requires arbitrary sweeps with rapid and abrupt variations of the optical frequency, the fixed reference oscillator is replaced by an arbitrary waveform generator, in order to create the appropriate reference signal. The laser is a DFB operating at 793.4 nm. The control and the corrected error signals are applied to the FET-current input of the laser. The systematic chirp nonlinearities are suppressed as much as possible by an open-loop pre-distortion technique [22, 25]. The nominal frequency is swept over 20 GHz within 250 µs, with a local slope varying from 25 GHz/ms to 400 GHz/ms. When the optical frequency sweep is locked to a reference electronic signal thanks to the opto-electronic feedback loop previously described, the error is reduced down to less than 1 MHz.

III. Experimental Results of the Analyser

In order to test the performances of the spectral analyzer, several RF generators and arbitrary waveforms generators have been used to simulate broadband and complex RF spectra. Two examples of spectrograms are presented in Fig. 4 and Fig. 5.

In Fig. 4, the crystal was programmed over 20 GHz and the frame rate of the photodetector was set to 10 kHz, while the integration time was 98 µs (the maximum possible for the

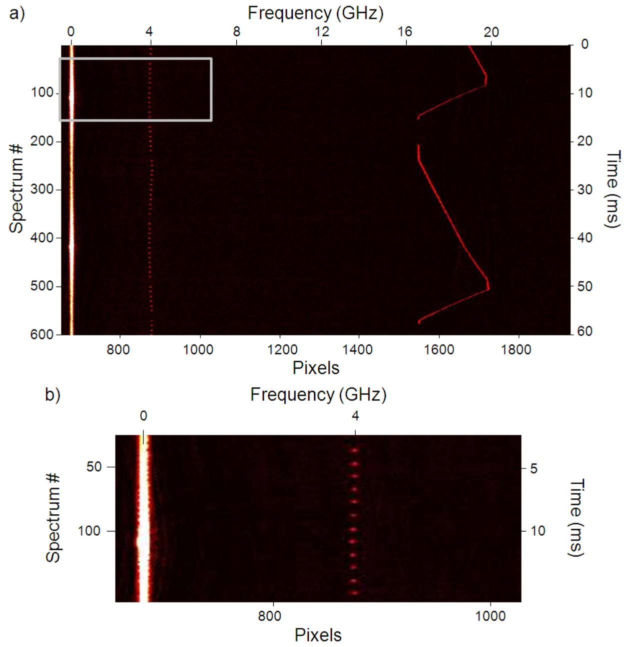

Fig. 4. Spectrogram over 20 GHz with a frame rate of 2 kHz, recorded over 60 ms. The experimental parameters are detailed in the text. (a) Whole spectrogram. (b) zoom of the previous spectrogram.

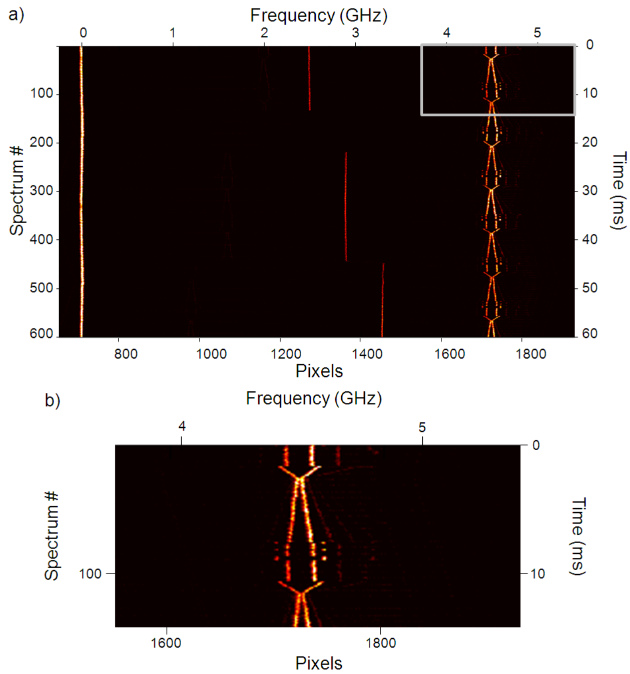

Fig. 5. Spectrogram over 5 GHz with a frame rate of 2 kHz, recorded over 60 ms. The experimental parameters are detailed in the text. (a) Whole spectrogram. (b) zoom of the previous spectrogram.

camera at this frame rate), leading to a probability of intercept of 98 %. A generator created a cw signal whose frequency was swept over 3.2 GHz within 30 ms, around 18.3 GHz. A second generator produced pulses at 4 GHz with a repetition rate of 2 kHz. As it can be seen on the spectrograms, the two signals are simultaneously analyzed with all their time-frequency features, with a spectral resolution of 50 MHz.

To illustrate the flexibility of the architecture, the crystal was then programmed for an analysis from 0 to 5 GHz, the frame rate of the photo-detector being kept to 10 kHz. A first generator produced a cw signal with frequency steps every 20 ms. A complex signal was created by an arbitrary waveform generator (bandwidth 125 MHz) and up-converted at 4.5 GHz. The programmed temporal sequence was the following: i) chirp from 0 to 50 MHz within 5 ms; ii) frequency hopping at 60 MHz and at 110MHz; (iii) chirp from 100 to 50 MHz within 1 ms. The spectrograms of Fig 5 illustrates the correct analysis of these signal by our set-up, with a spectral resolution being now below 20 MHz.

By using an all-optical compensation scheme on the signal beam, we have been able to extend the probability of intercept to 100 %. We also preliminary estimated the dynamic range of our architecture to be above 35 dB.

IV. Conclusion

We experimentally demonstrated a RF spectrum analyzer based on the so called "rainbow architecture" which enables to monitor and record the spectrum of complex microwave signals over an instantaneous bandwidth of 20 GHz, with a time resolution below 100 µs, 400 resolvable frequency components and a probability of intercept of 100 %. This architecture allows easy further improvements: the time resolution can be improved by using higher frame rate photo-detector, and the number of spectral channels can be increased by implementing for example the 2D geometry proposed in [20].

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